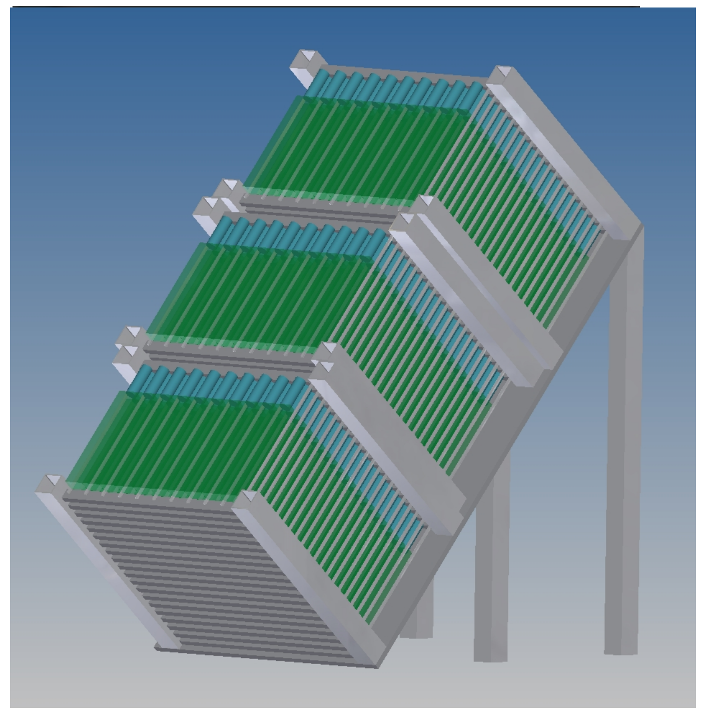


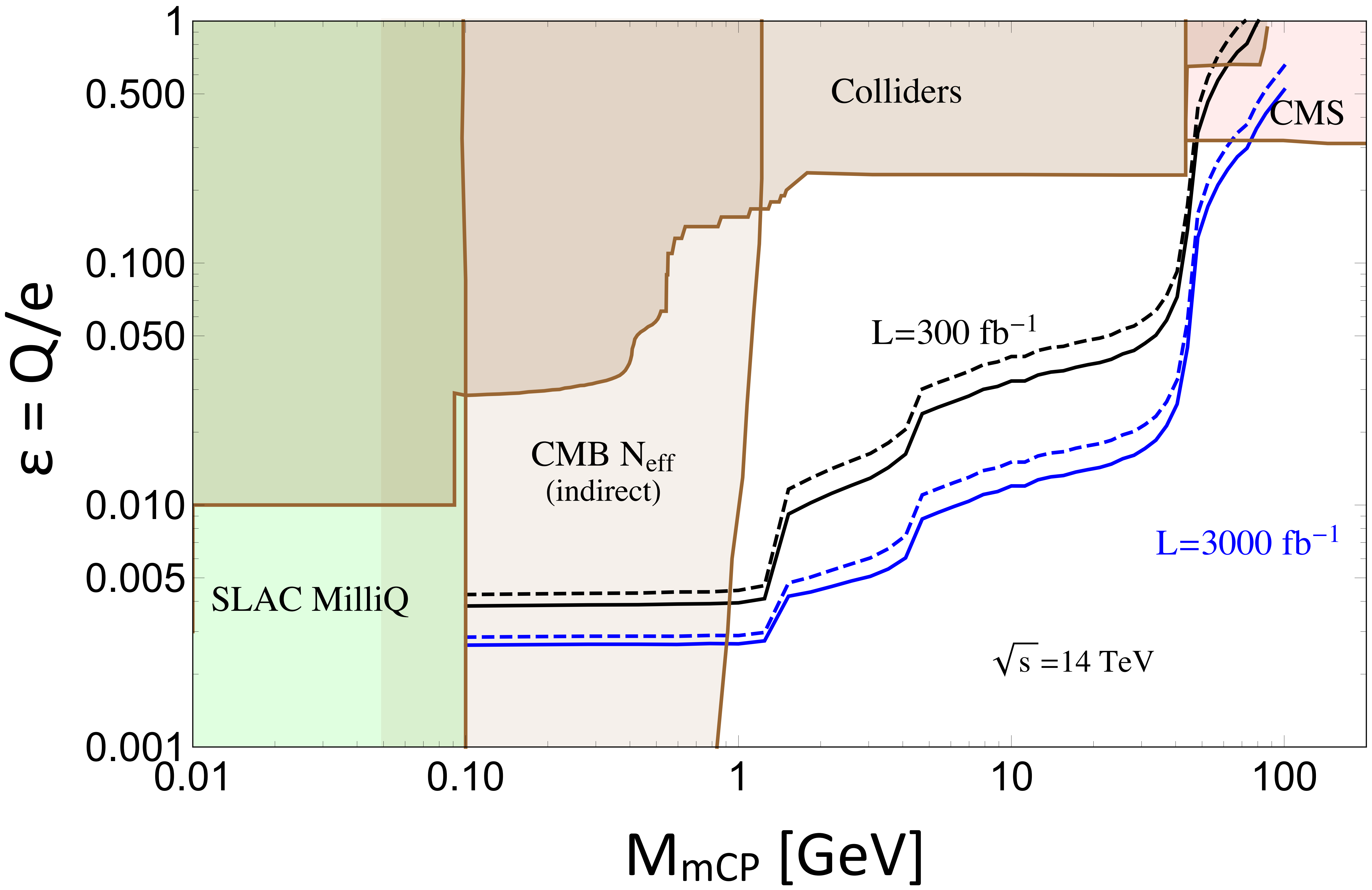
The milliQan Experiment: Search for milli-charged Particles at the LHC

Jae Hyeok Yoo (UC Santa Barbara)
on behalf of milliQan Collaboration

07/07/2018

ICHEP2018 Seoul

milliQan experiment



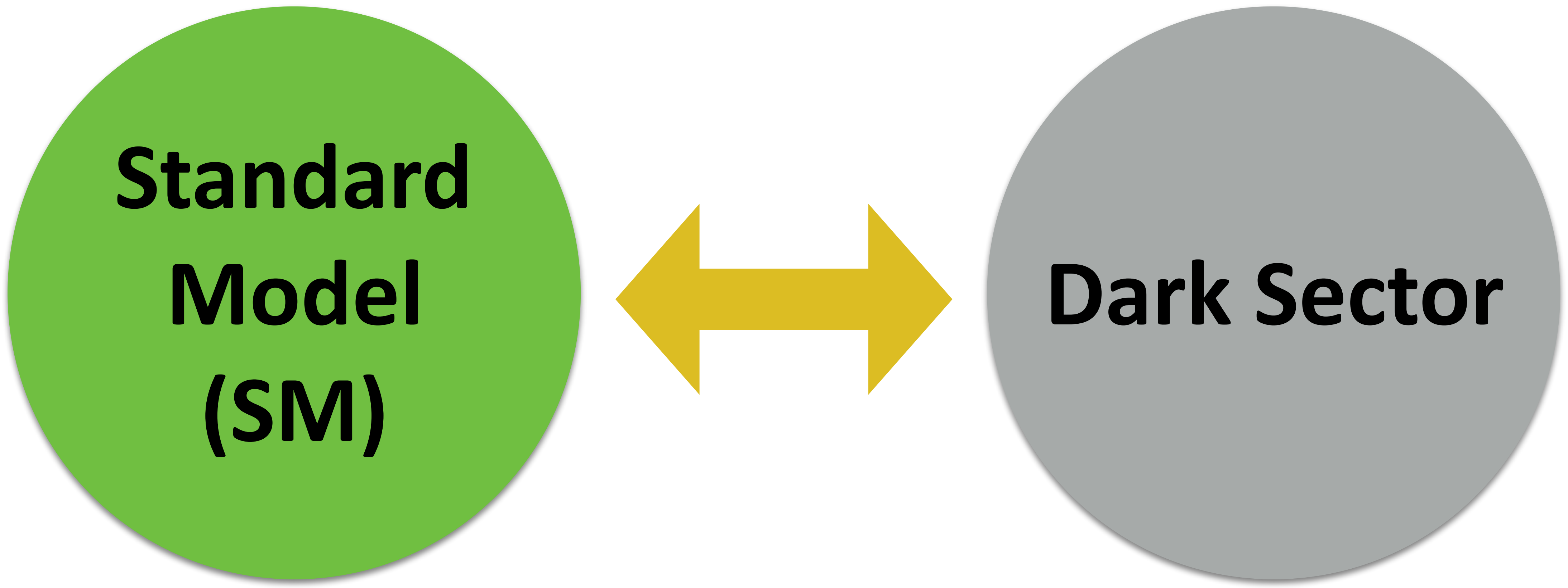
- No evidence for new physics at the LHC
  - Any phase space we might not be exploring?
- milliQan experiment searches for milli-charged particles (mCP) produced at the LHC
  - Existing detectors miss such particles due to small energy deposits and large background
- Limits from low energy and direct CMS/ ATLAS searches cover only low mass and high charge region
  - M_{mCP}>1 GeV and Q<0.3e region unexplored
- milliQan provides a unique opportunity to explore this region

milli-charged particles

- There are multiple ways to get mili-charged particles
- A new U(1) in dark sector with massless dark-photon (A') and massive dark-fermion (ψ)

$$\mathcal{L}_{\text{dark sector}}$$
$$= -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\not{\partial} + ie'\not{A}' + iM_{\text{mCP}}\right)\psi$$

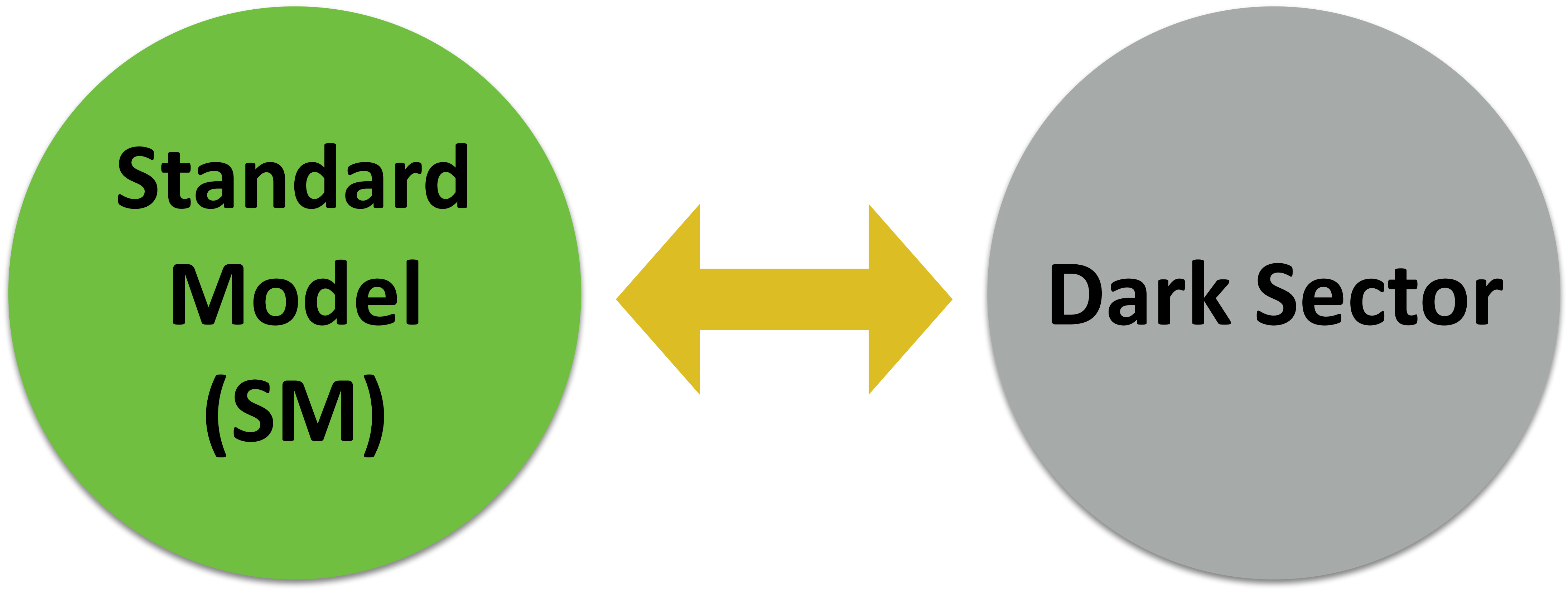
milli-charged particles



$$\mathcal{L}_{\text{dark sector}}$$
$$= -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\not{\partial} + ie'\not{A}' + iM_{\text{mCP}}\right)\psi$$
$$- \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$$

- There are multiple ways to get mili-charged particles
- A new U(1) in dark sector with massless dark-photon (A') and massive dark-fermion (ψ)
- A' and B kinetically mix

milli-charged particles



- There are multiple ways to get mili-charged particles
- A new U(1) in dark sector with massless dark-photon (A’) and massive dark-fermion (ψ)
- A’ and B kinetically mix
- Charge of ψ is proportional to mixing (κ)

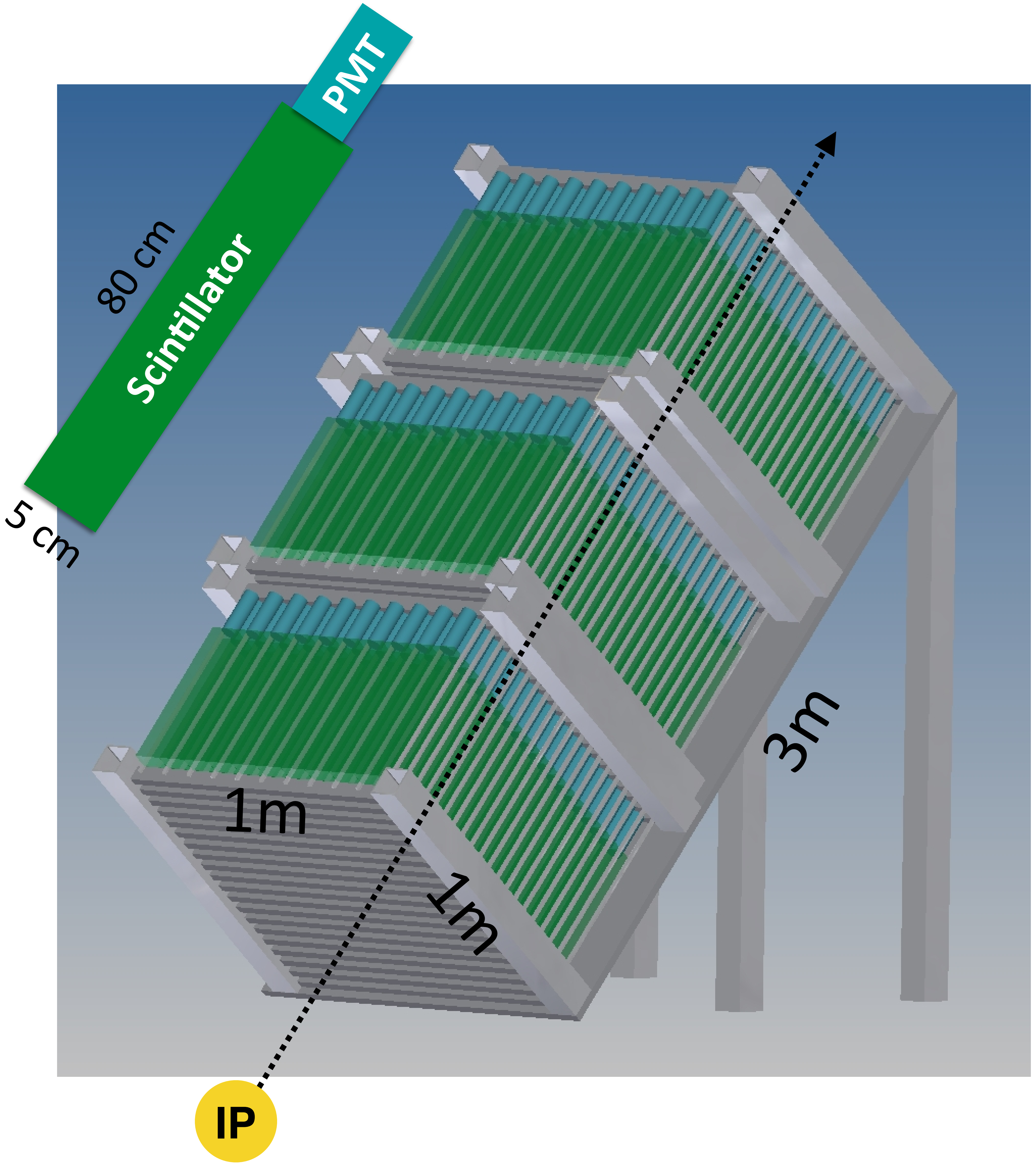
$$\mathcal{L}_{\text{dark sector}} = -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\not\partial + ie'\not A' + iM_{\text{mCP}}\right)\psi - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$$

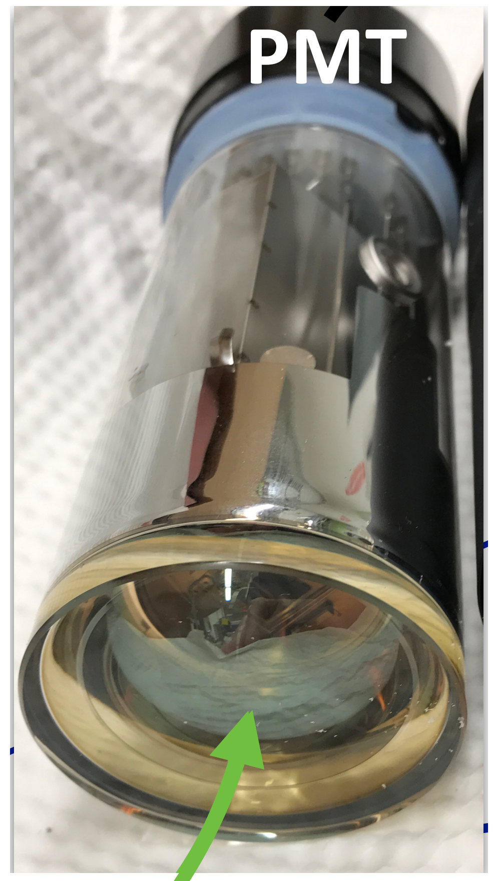
$$A'_\mu \to A'_\mu + \kappa B_\mu$$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\not\partial + ie'\not A' + i\kappa e'\not B + iM_{\text{mCP}}\right)\psi$$

κ = 10^{-3} - 10^{-2} : milli-charge

Detector concept





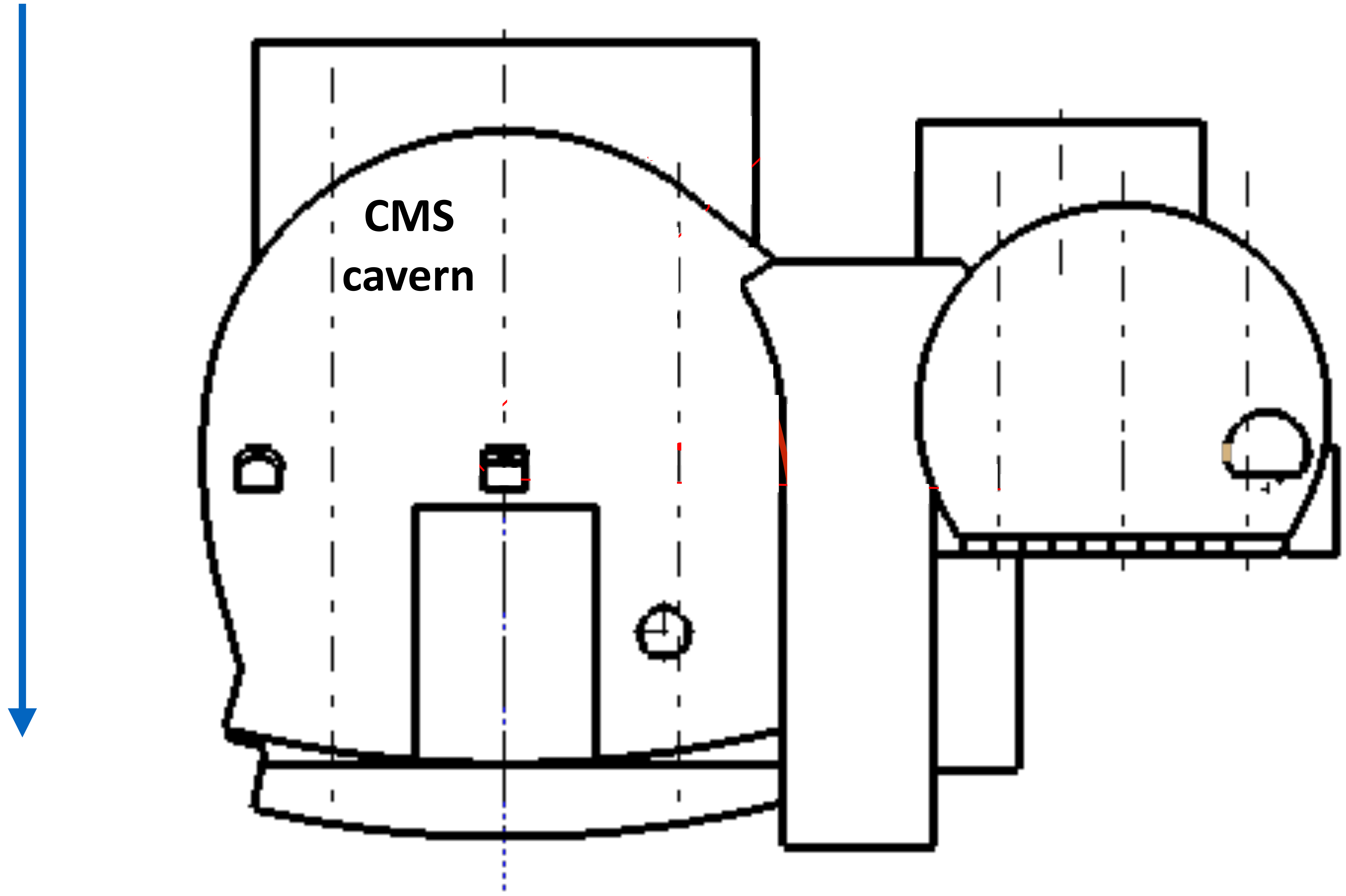
- With charge down to 10^{-3}e, dE/dx is 10^{-6} of Q=1e particles
  - EM interaction proportional to Q^2
  - need large, active, sensitive area to produce signals, even as small as single photon
- Composed of 3 layers of 80x5x5 cm scintillator arrays pointing back to CMS IP
  - particles from IP should go through all 3 layers: reduces random combinatoric backgrounds
- Light converted/amplified by photomultiplier tube (PMT)

Detector location

- Ideal location for detector
  - shield cosmics: underground
  - shield beam particles: thick material
- Found a place that satisfies both

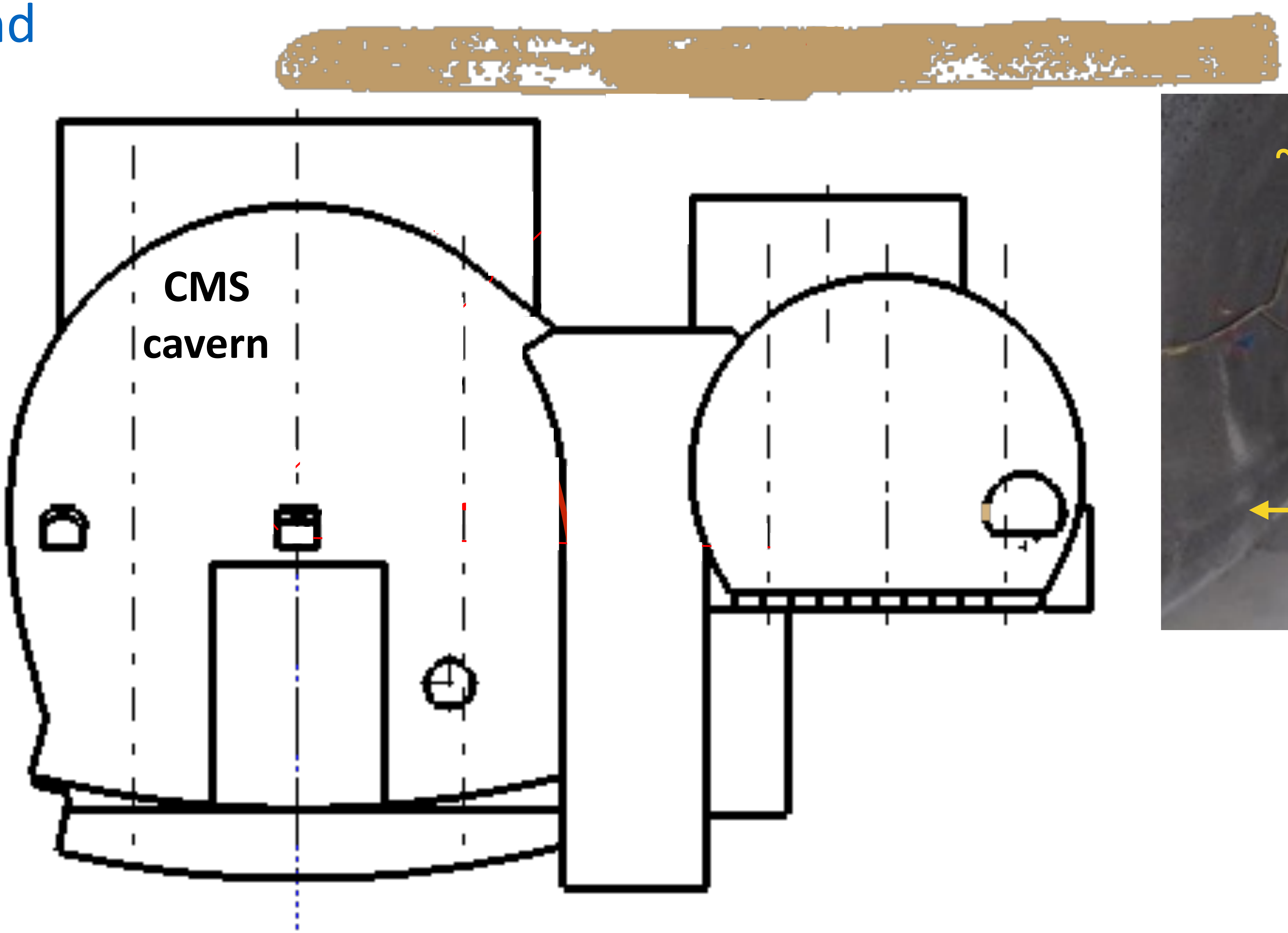
Detector location

100m
underground

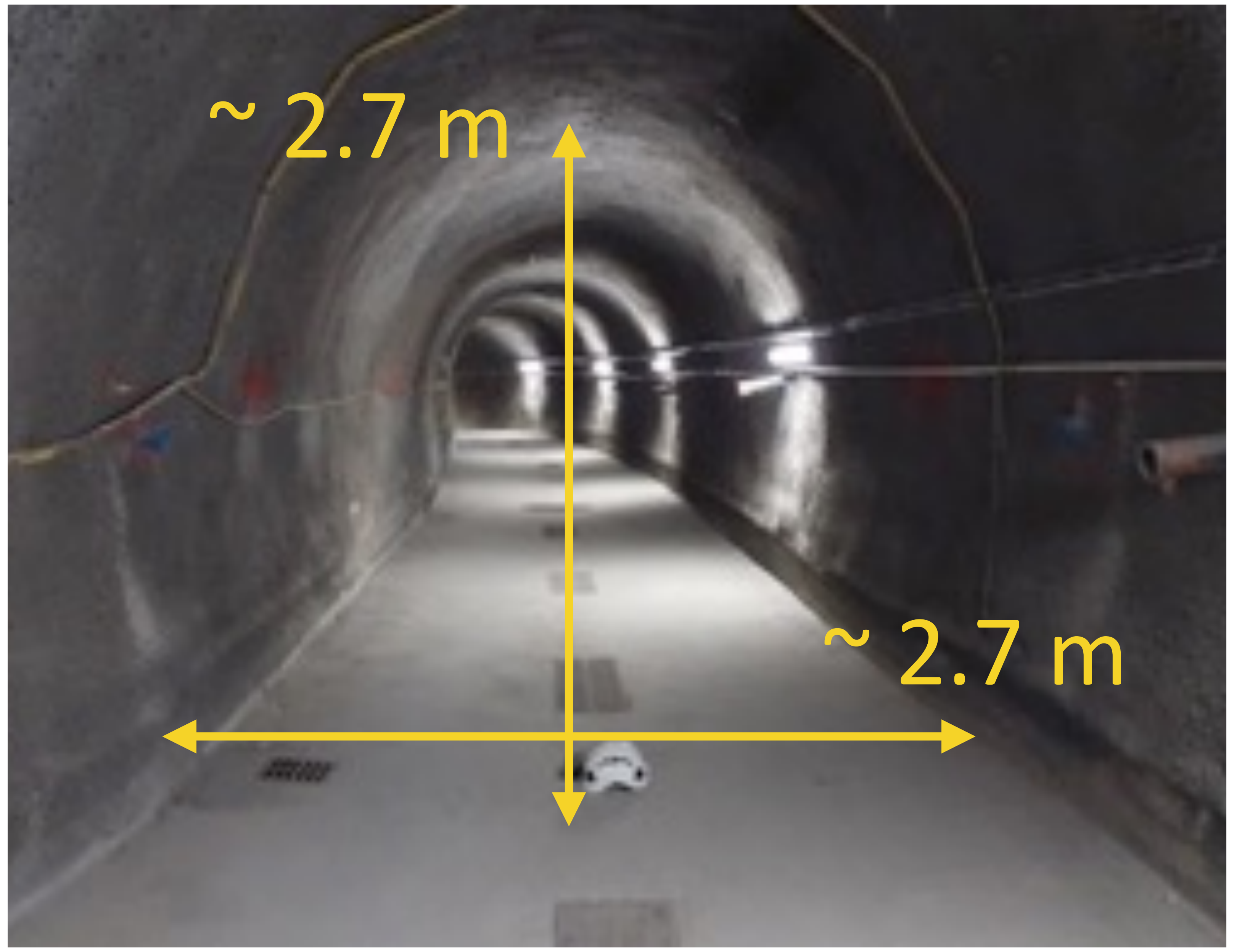


Detector location

100m underground

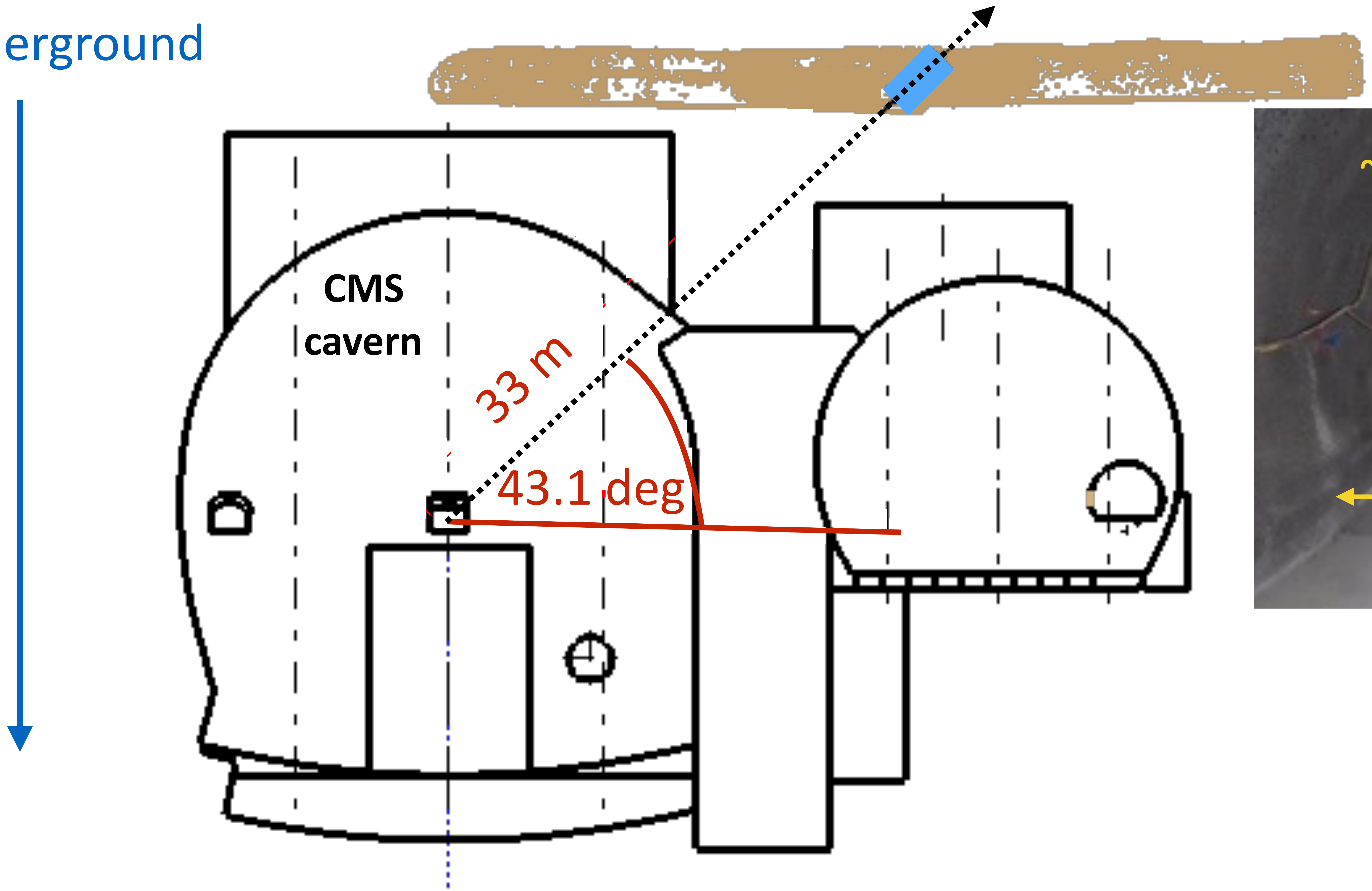


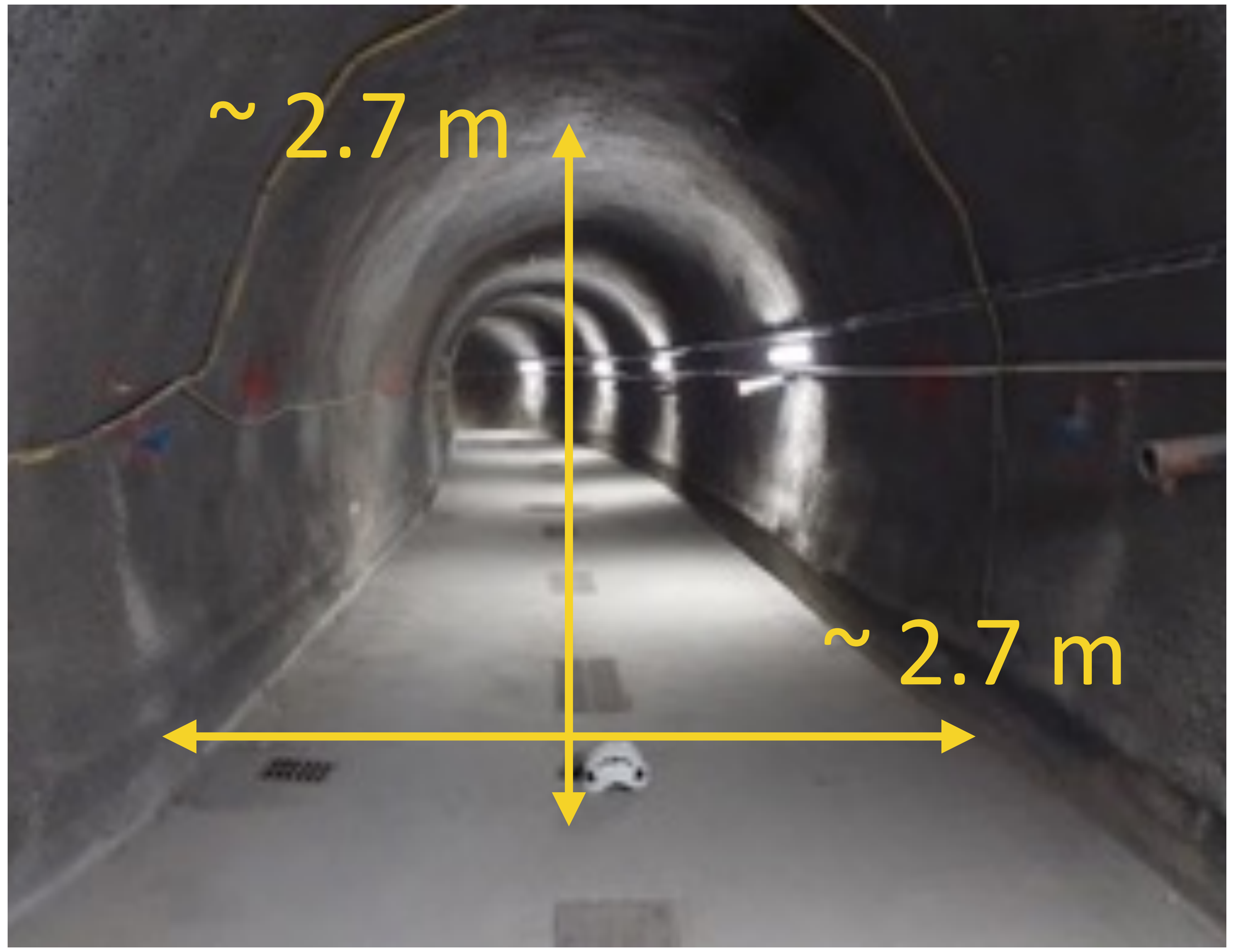
Drainage gallery



Detector location

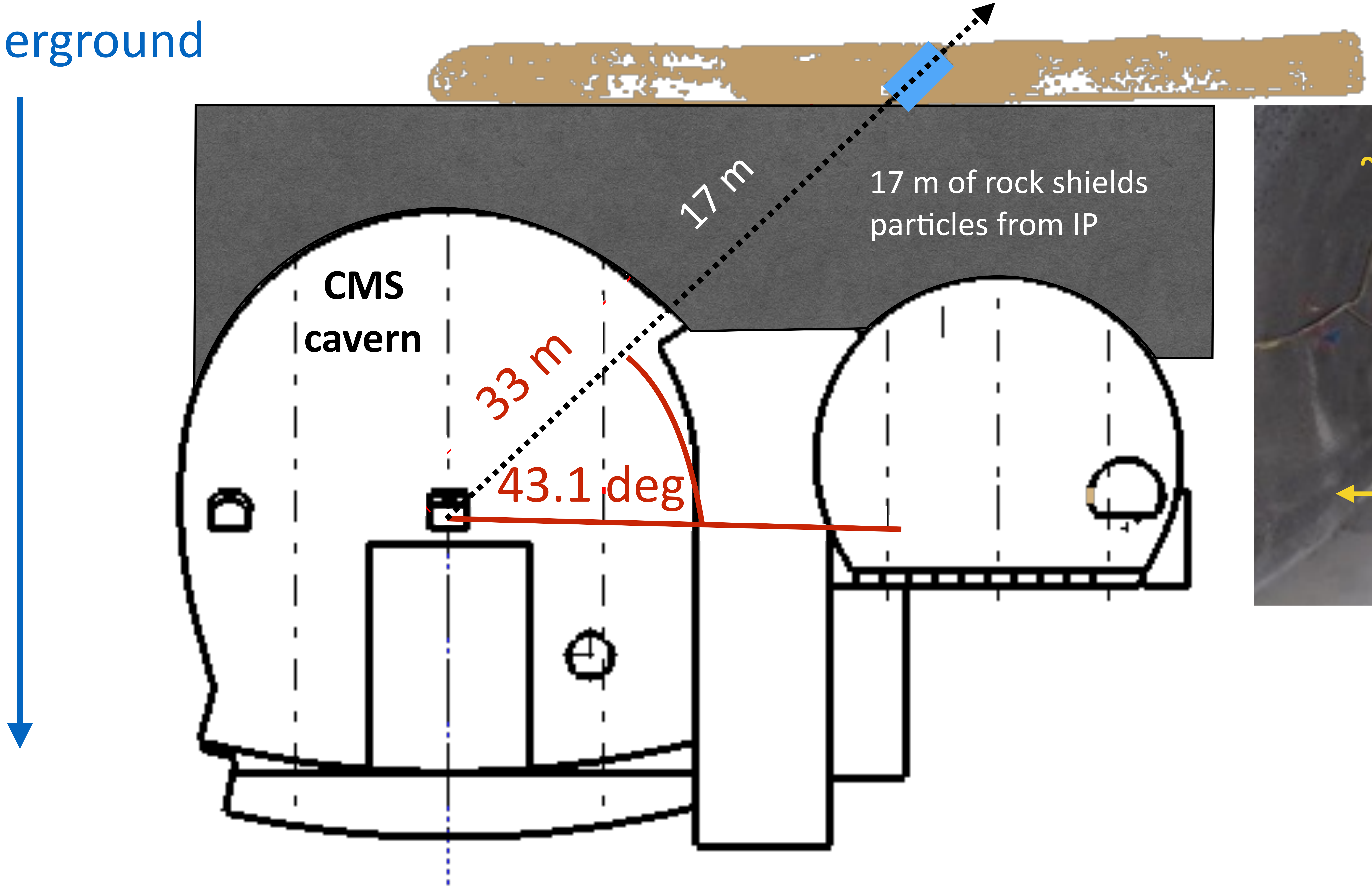
100m underground



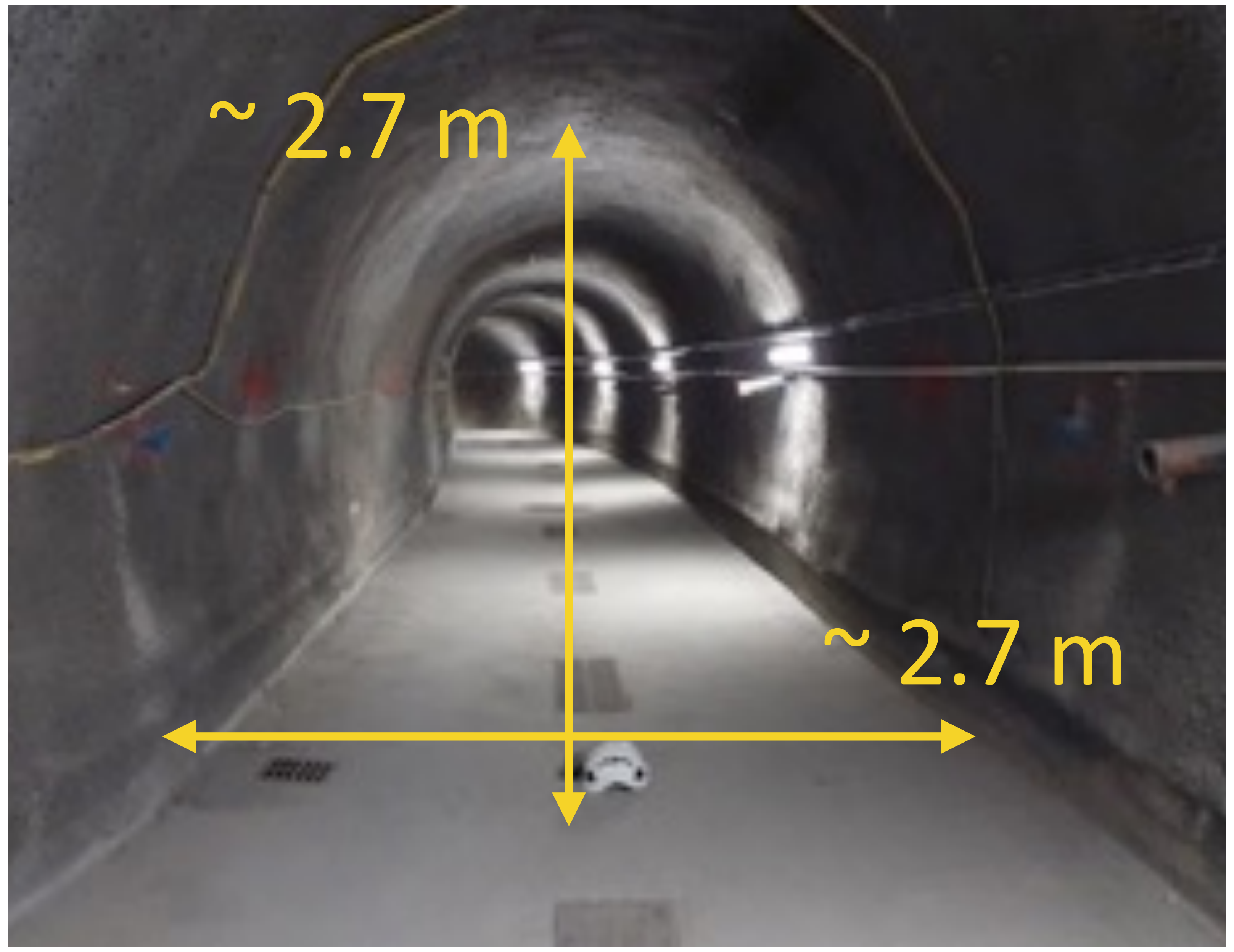


Detector location

100m underground

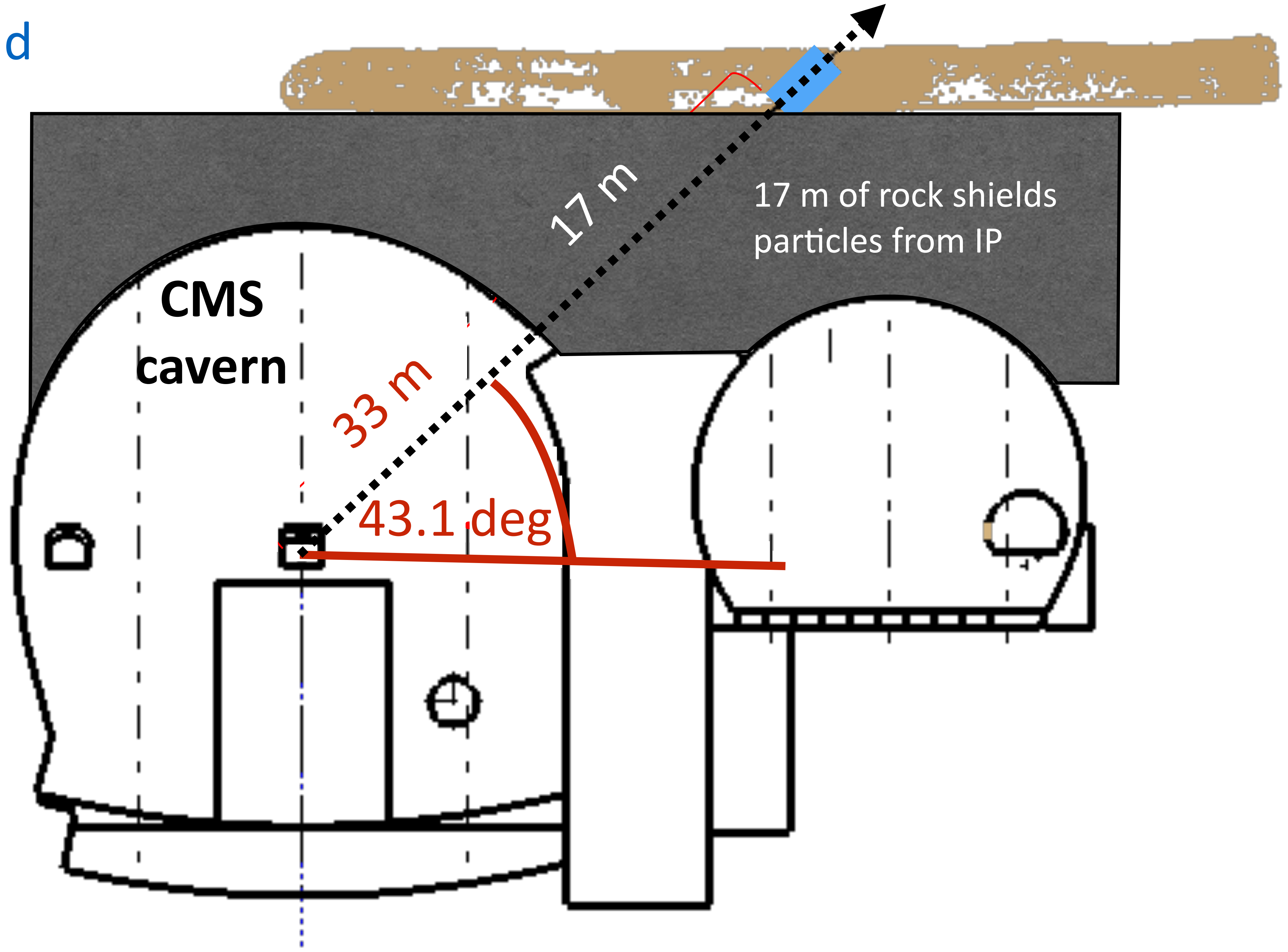


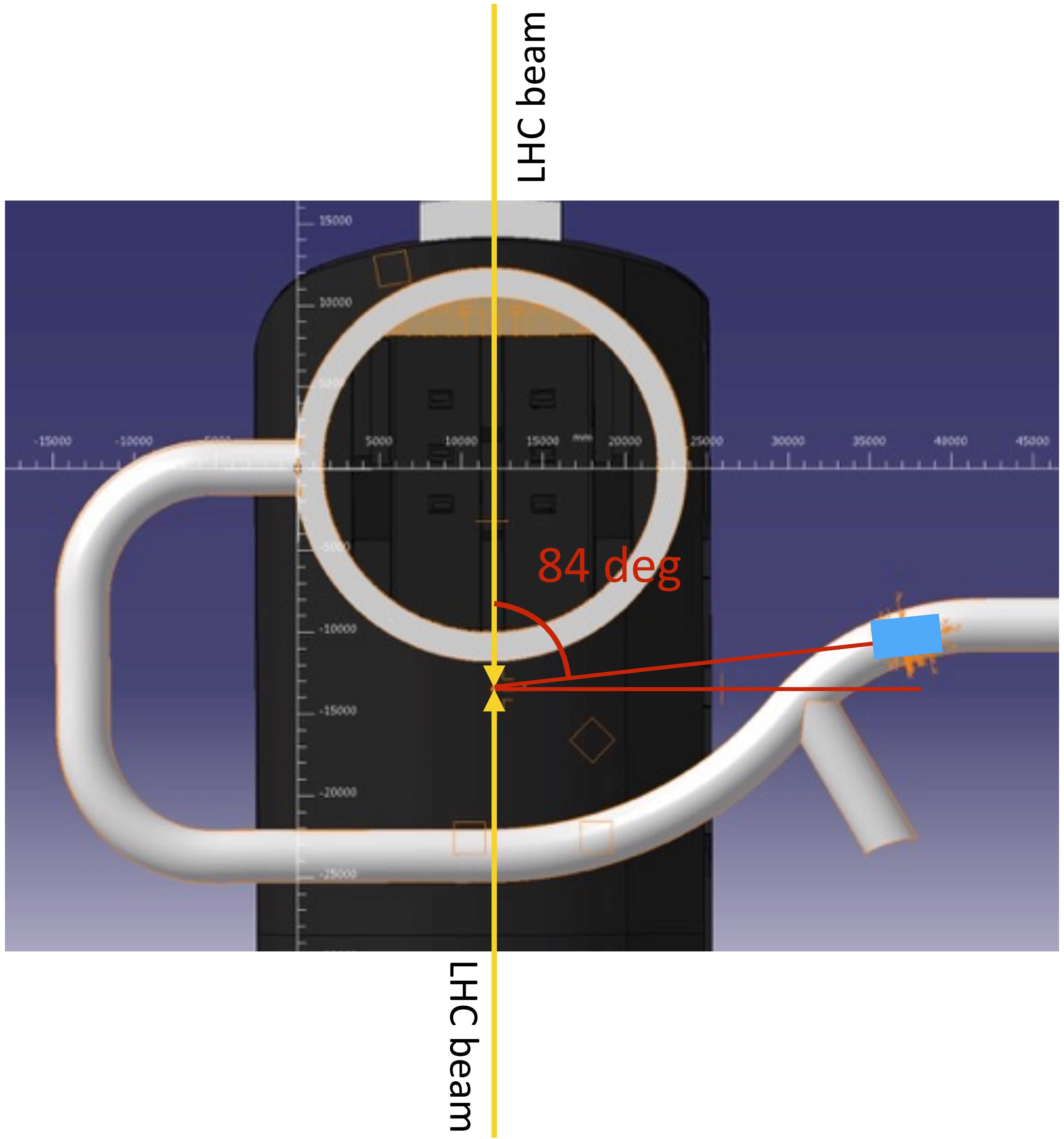
Drainage gallery



Detector location

100m underground

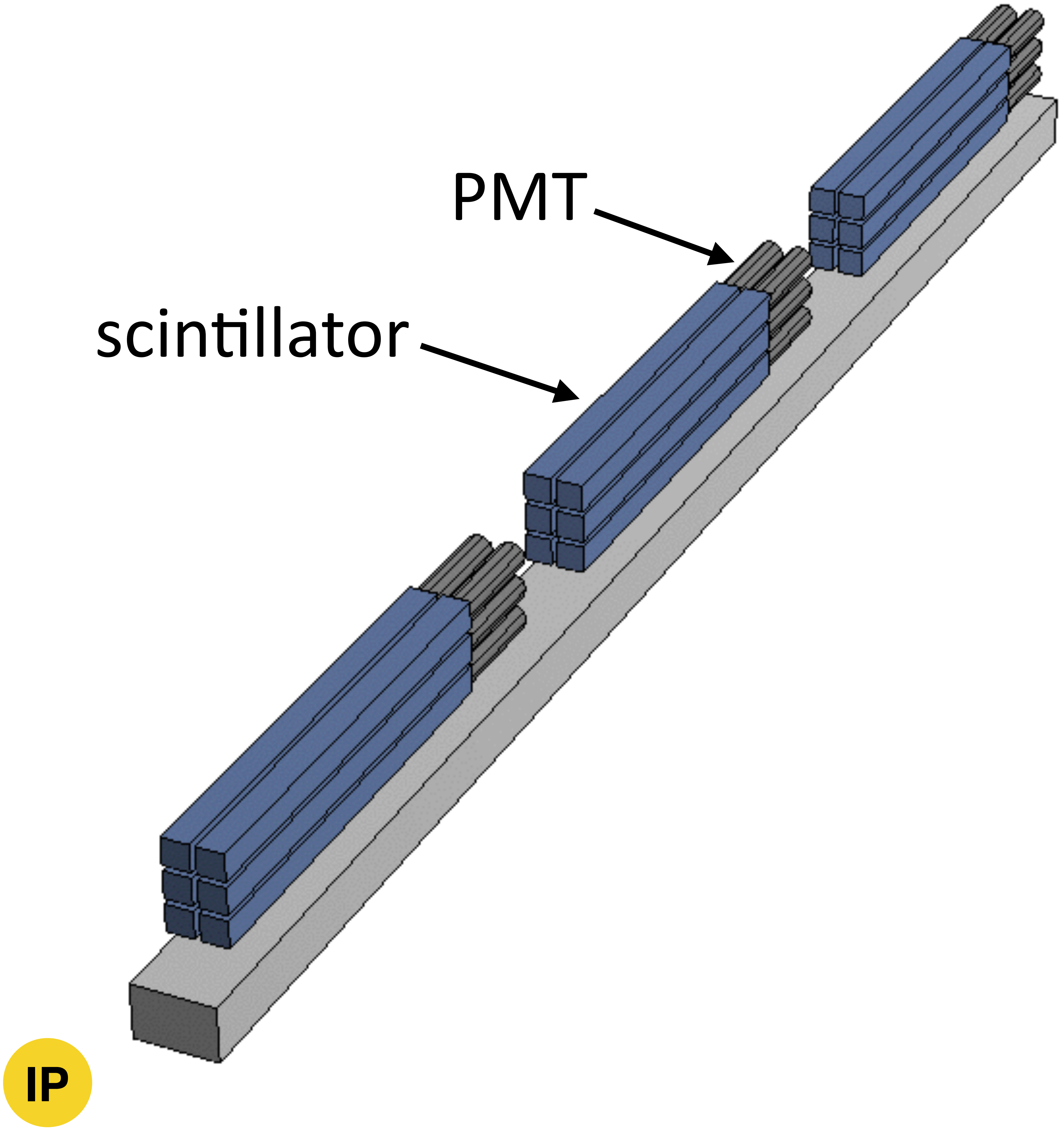




Demonstrator

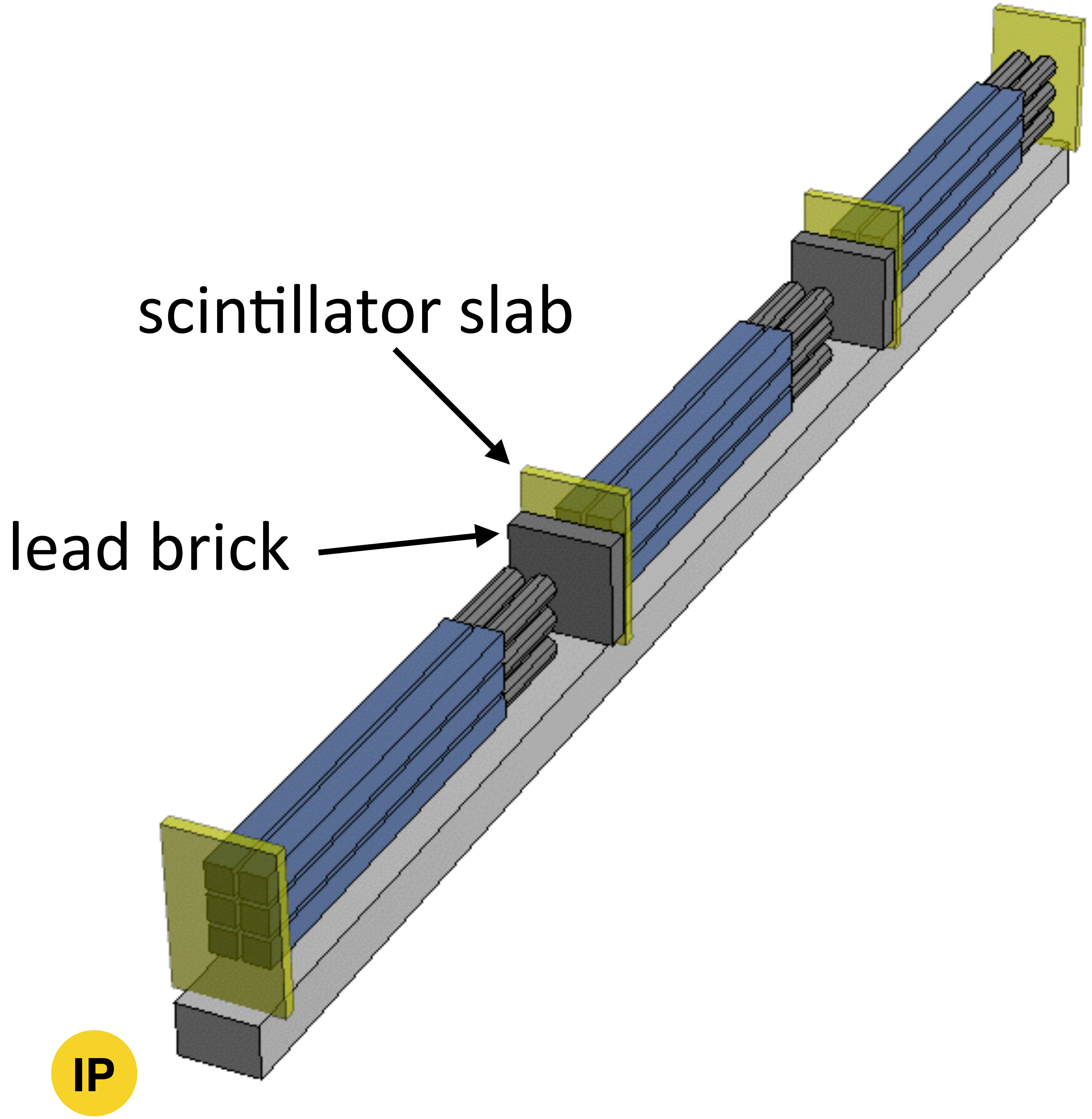
- In order to verify the feasibility and optimize the design of the experiment thoroughly, ~1% of the detector is installed as a "demonstrator"

Demonstrator



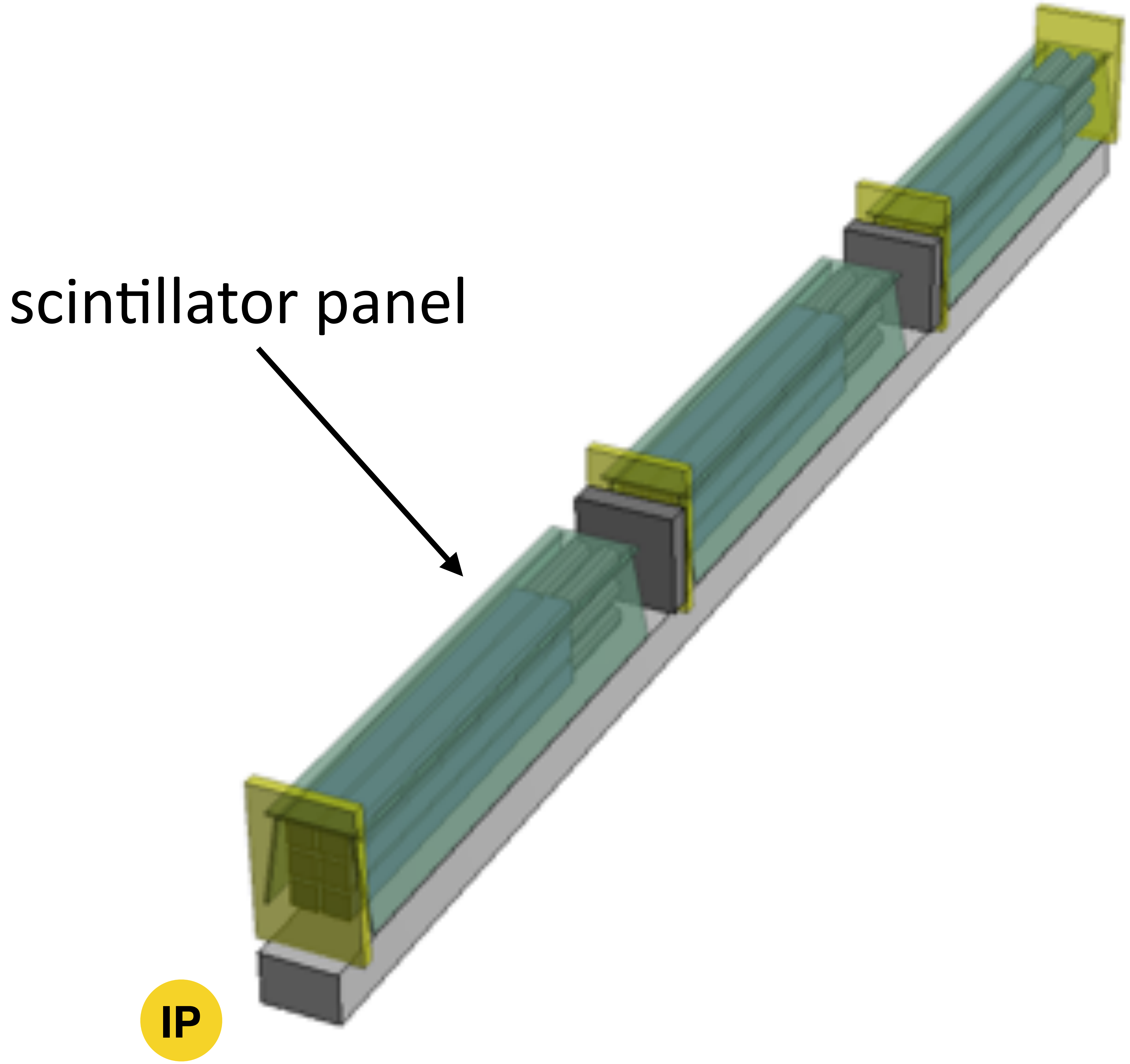
- In order to verify the feasibility and optimize the design of the experiment thoroughly, ~1% of the detector is installed as a "demonstrator"
- 3 layers of 2x3 scintillator+PMT

Demonstrator



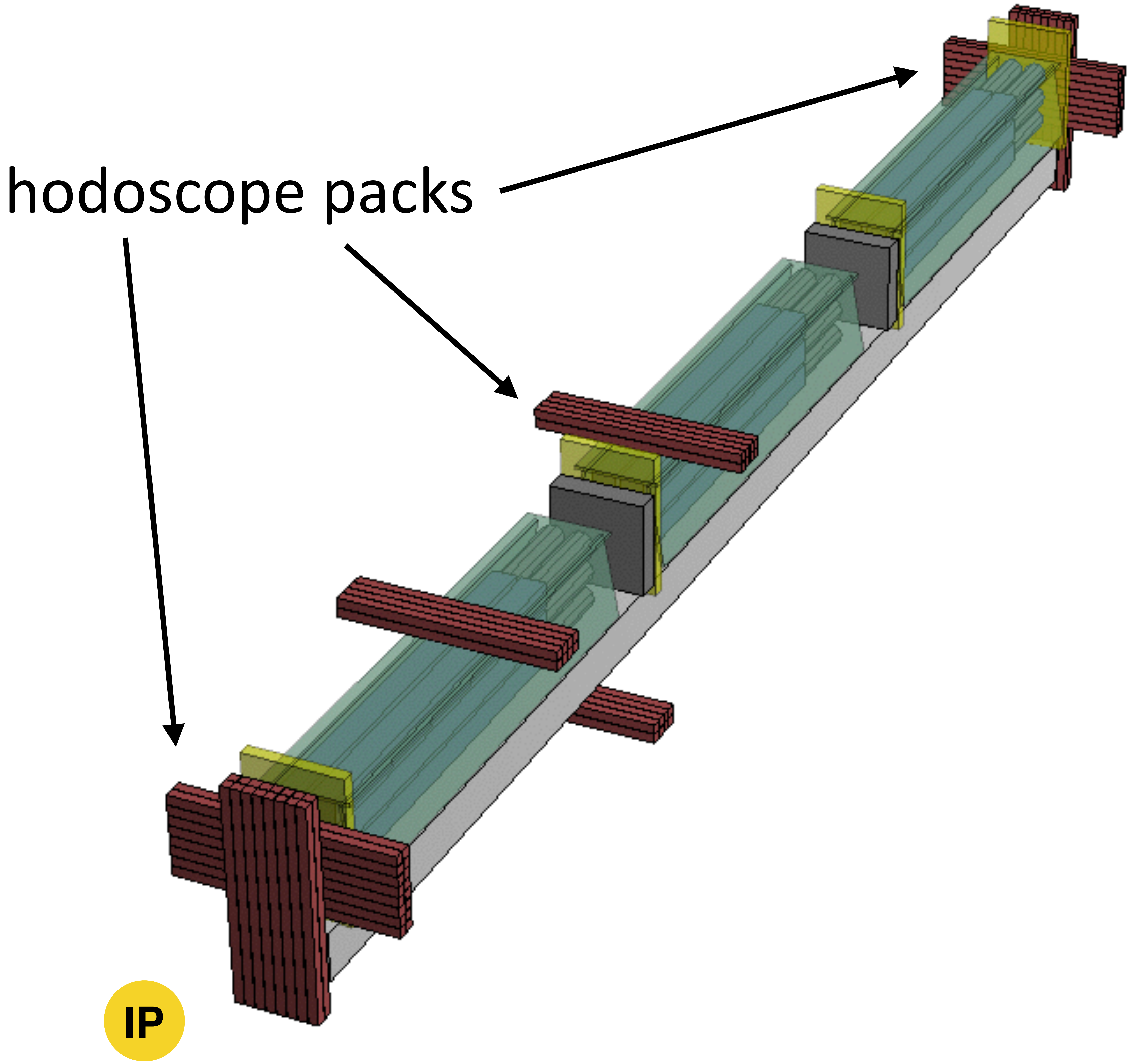
- In order to verify the feasibility and optimize the design of the experiment thoroughly, ~1% of the detector is installed as a "demonstrator"
- 3 layers of 2x3 scintillator+PMT
- Scintillator slabs and lead bricks
  - Tag thru-going particles, get time info, shield radiation

Demonstrator



- In order to verify the feasibility and optimize the design of the experiment thoroughly, ~1% of the detector is installed as a "demonstrator"
- 3 layers of 2x3 scintillator+PMT
- Scintillator slabs and lead bricks
  - Tag thru-going particles, get time info, shield radiation
- Scintillator panels to cover top and sides
  - Tag/reject cosmic muons

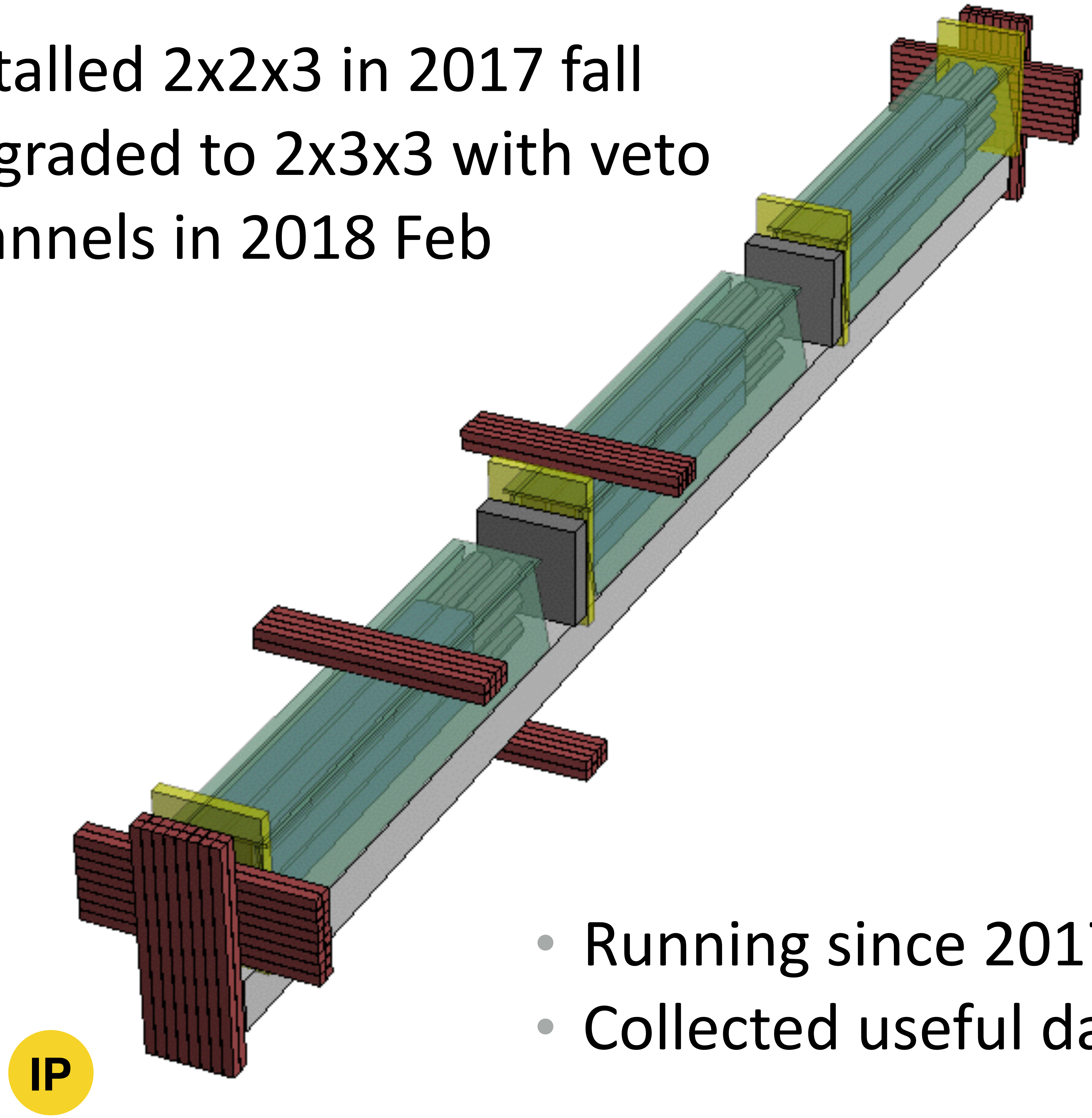
Demonstrator



- In order to verify the feasibility and optimize the design of the experiment thoroughly, ~1% of the detector is installed as a “demonstrator”
- 3 layers of 2x3 scintillator+PMT
- Scintillator slabs and lead bricks
  - Tag thru-going particles, get time info, shield radiation
- Scintillator panels to cover top and sides
  - Tag/reject cosmic muons
- Hodoscope packs
  - Get tracks of beam/cosmic muons

Demonstrator

- Installed 2x2x3 in 2017 fall
- Upgraded to 2x3x3 with veto channels in 2018 Feb



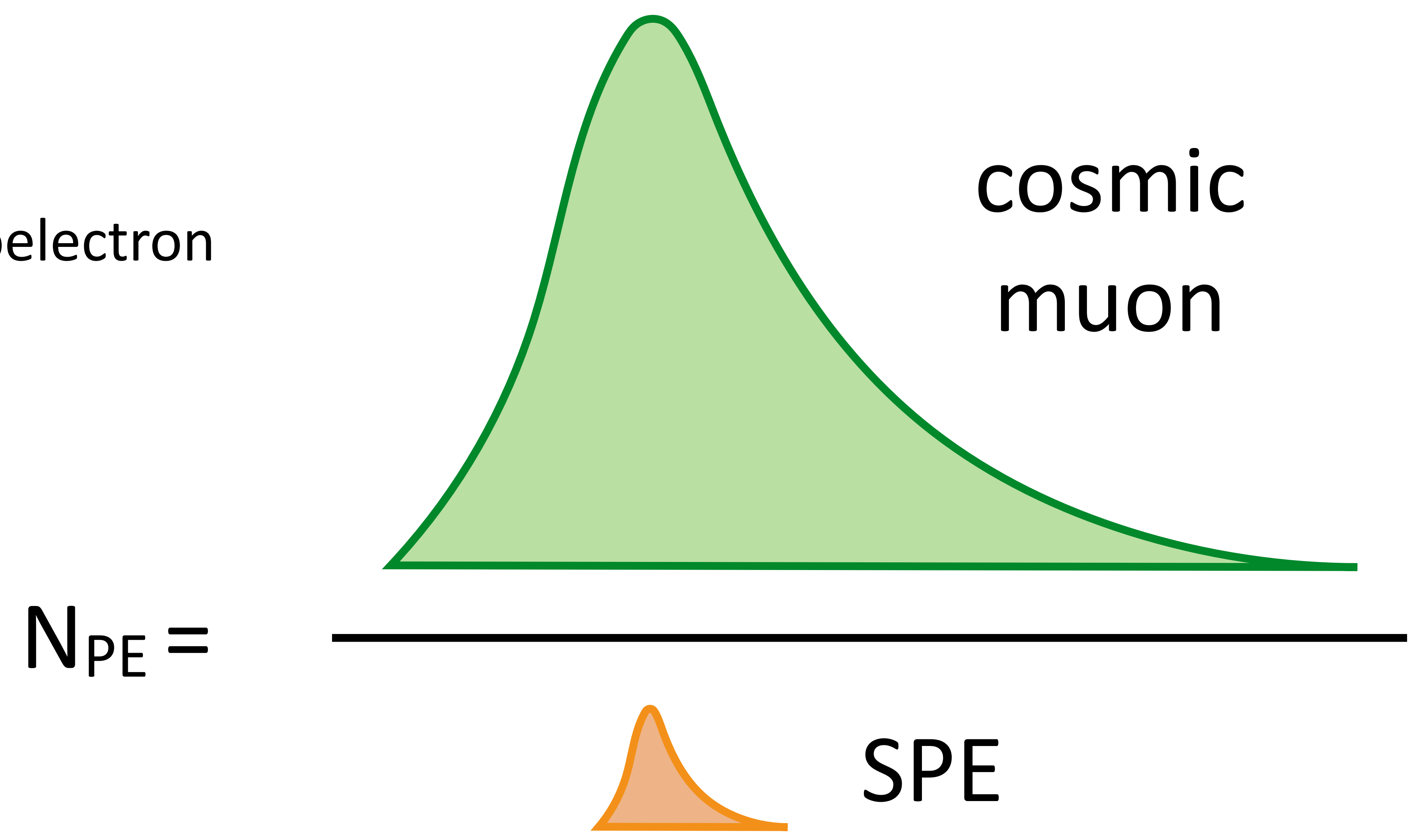
- Running since 2017 fall
- Collected useful data

Demonstrator results: in situ charge calibration

- Important because it tells us how small charge the MQ can detect
- Calculate N_{PE} for cosmic muon (Q=1e)
  - N_{PE} = Pulse area (cosmic muon) / Pulse area (SPE)

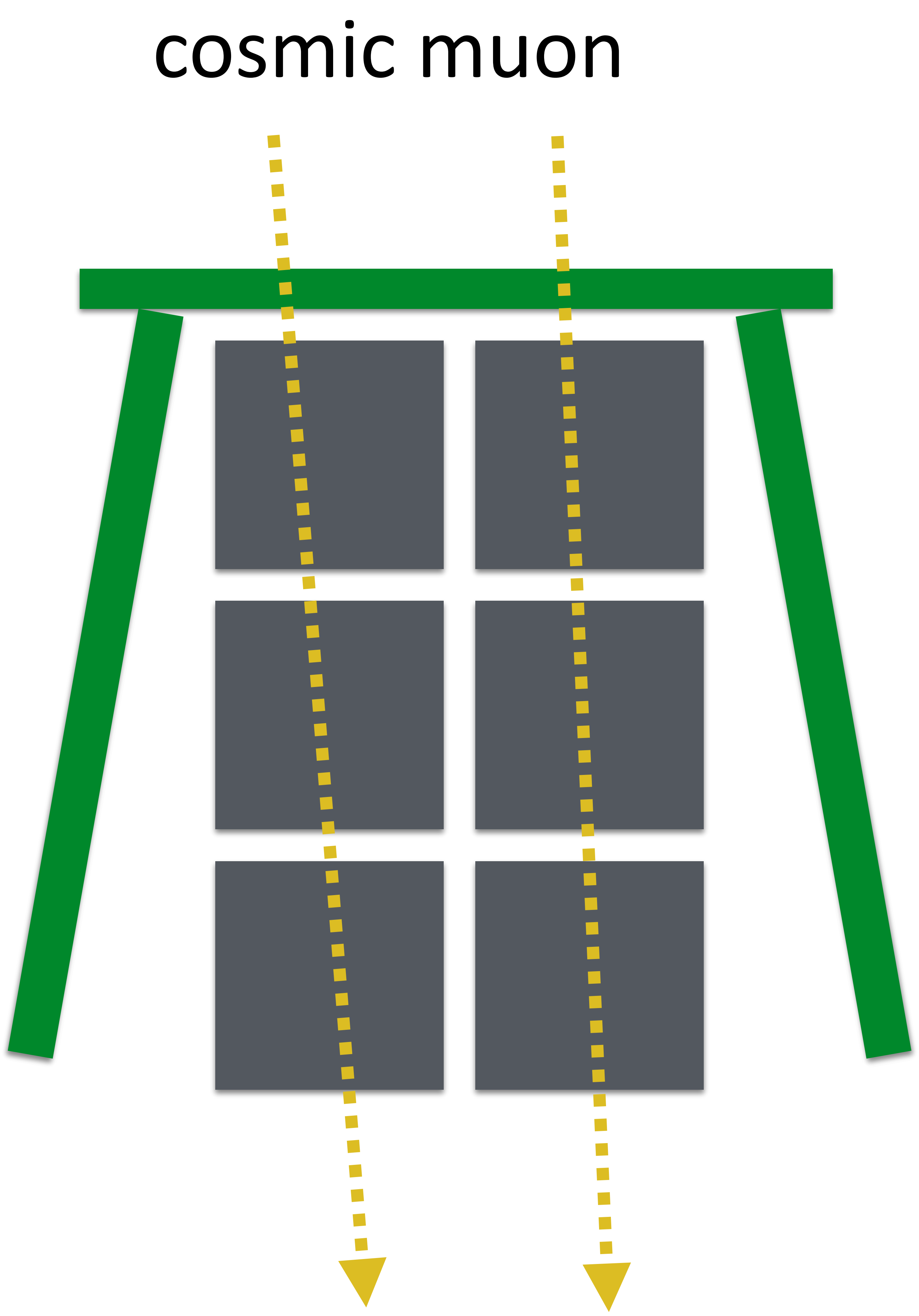
single photoelectron

- Extrapolate it to fractional charges by Q^2

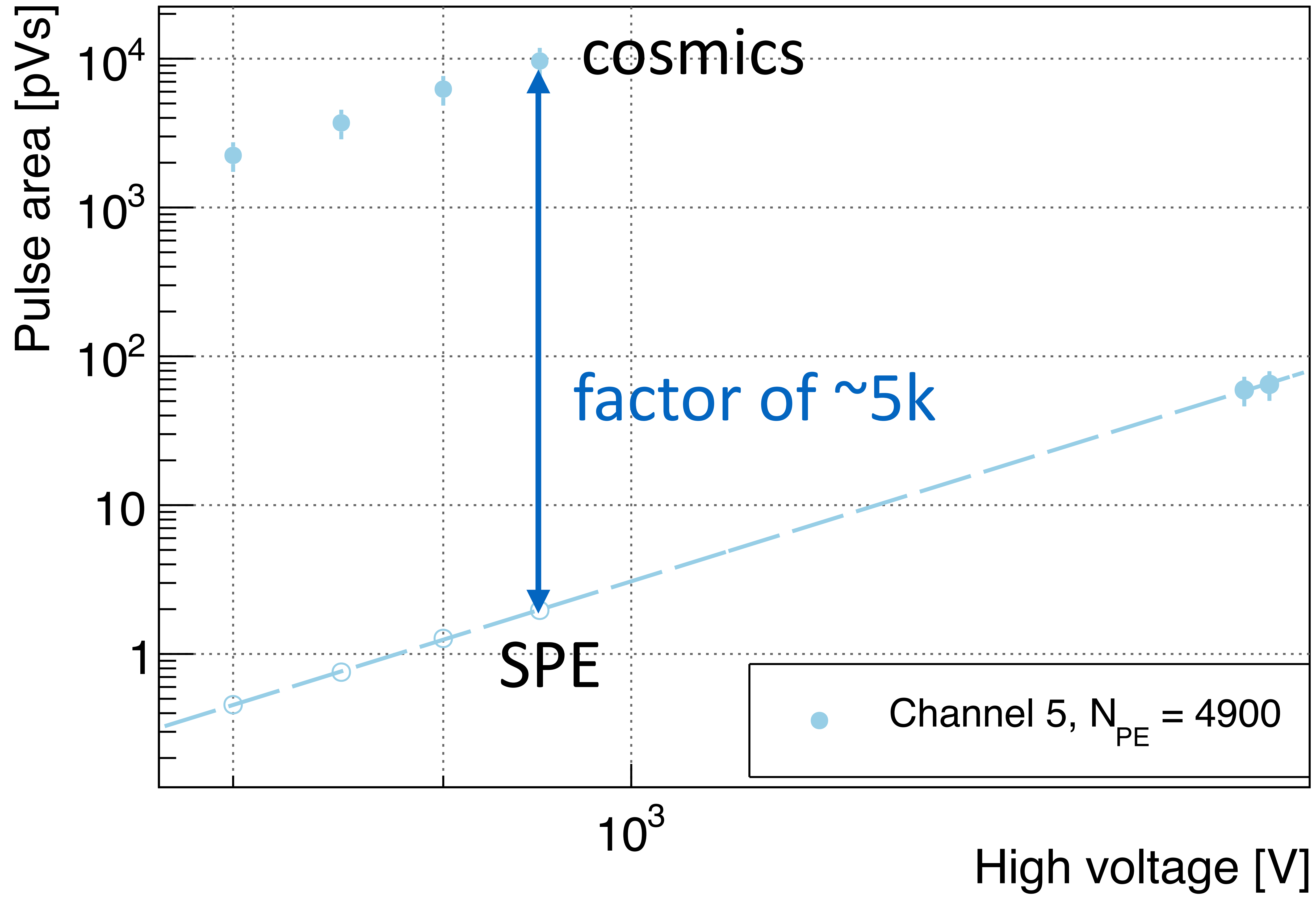


Demonstrator results: in situ charge calibration

- Important because it tells us how small charge the MQ can detect
- Calculate N_{PE} for cosmic muon (Q=1e)
  - N_{PE} = Pulse area (cosmic muon) / Pulse area (SPE)
- Extrapolate it to fractional charges by Q^2
- Cosmic muons from vertical path
- SPE from afterpulses
  - SPE pulse area measurement also done on the bench as a validation



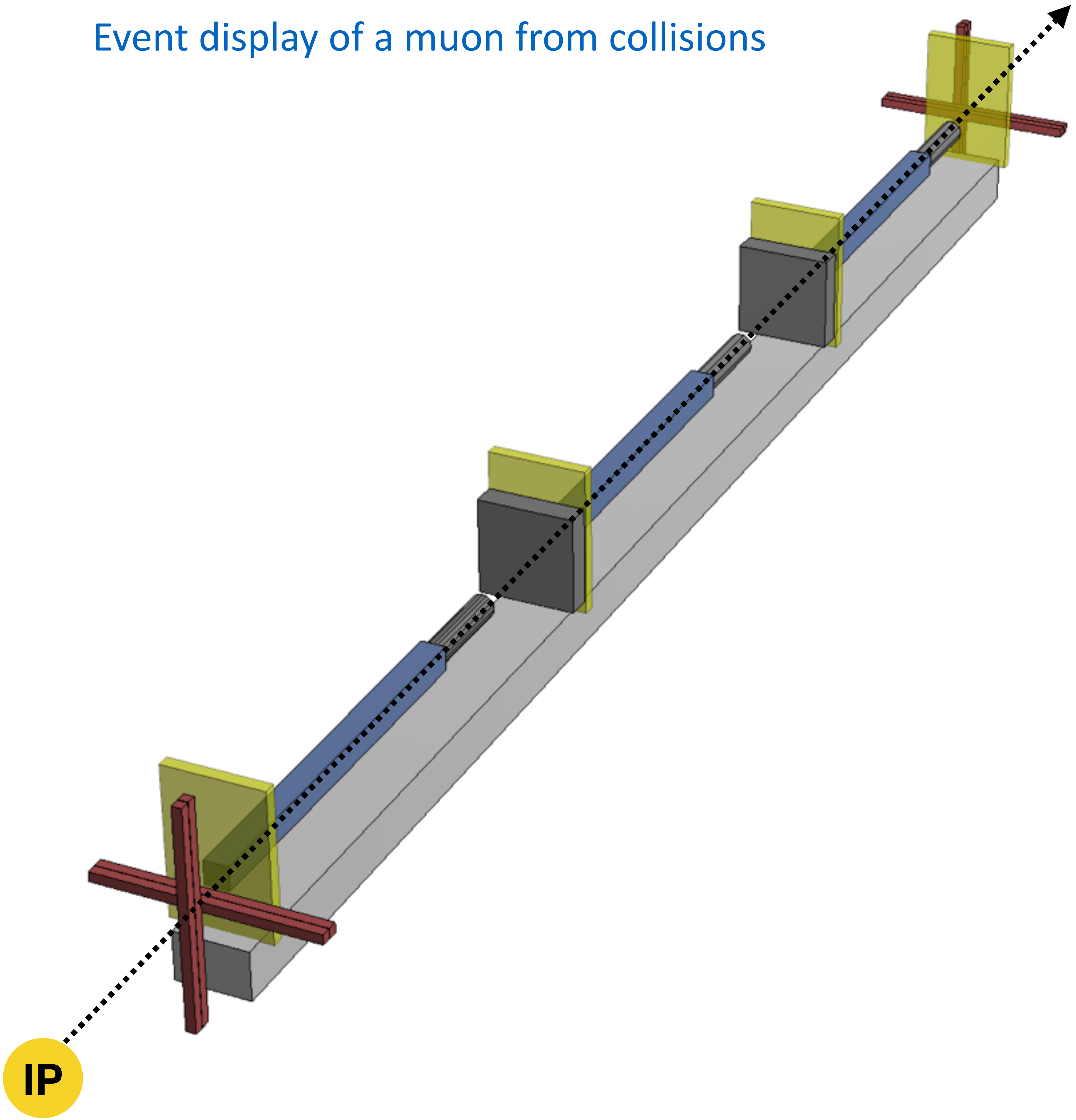
Demonstrator results: in situ charge calibration



- Pulse area as a function of HV for a PMT
- N_{PE} for Q=1e is ~5k
- Flight distance of cosmic muons in scintillator is 5 cm
- For through-going muons, the flight distance is 80 cm
- N_{PE} for thru-going muon is 5k x 80/5 = 80k
- Since N_{PE} is proportional to Q^2
  - N_{PE} = 1 for Q ~ 0.003e
- Consistent with full Geant4 simulation results

Demonstrator results: beam muons

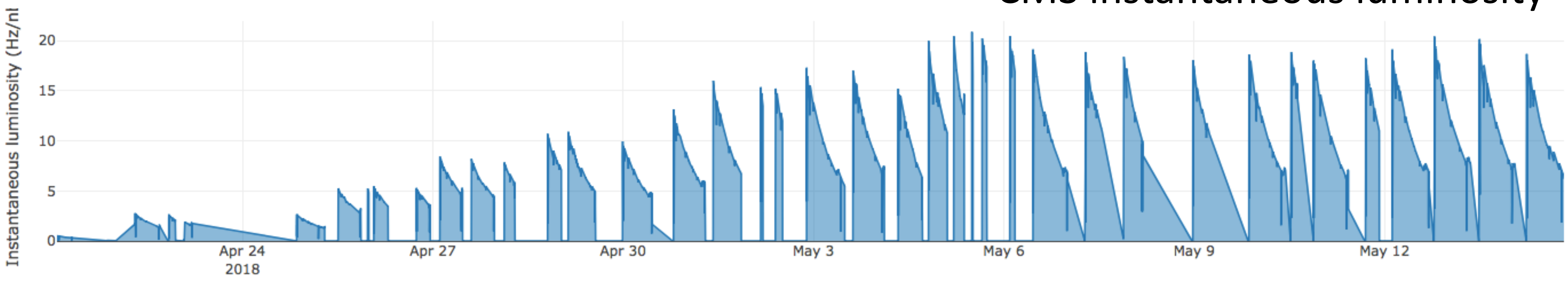
Event display of a muon from collisions



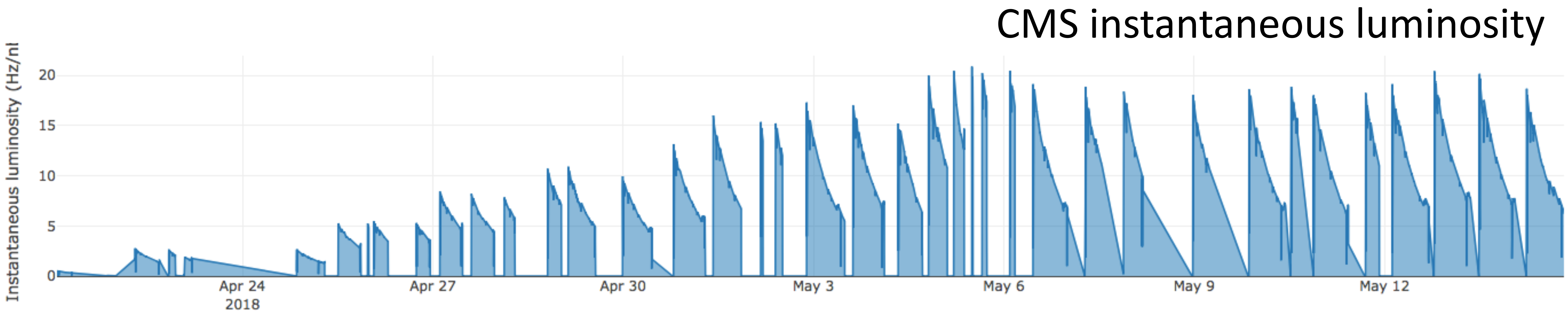
- Understand the demonstrator using muons from collisions
  - alignment, triggering, timing calibration, etc

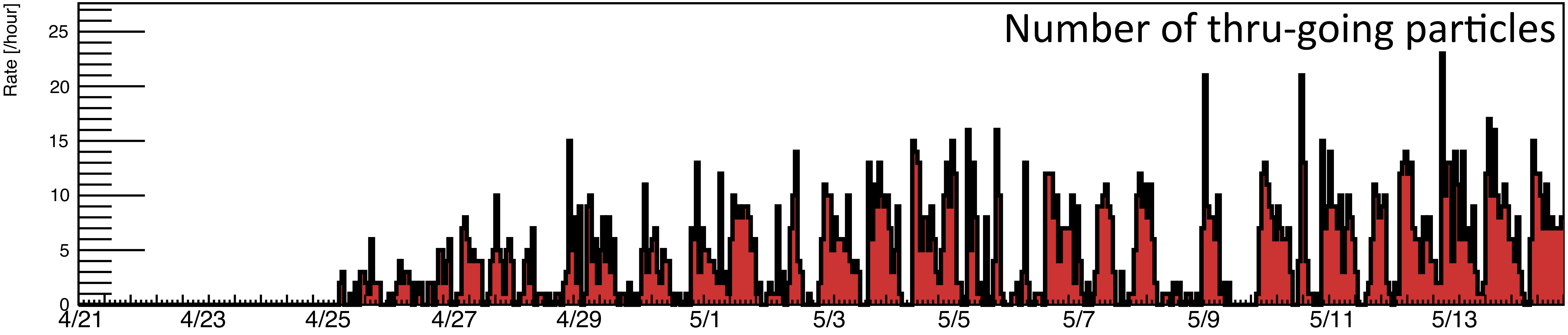
Demonstrator results: beam muon occupancy

CMS instantaneous luminosity

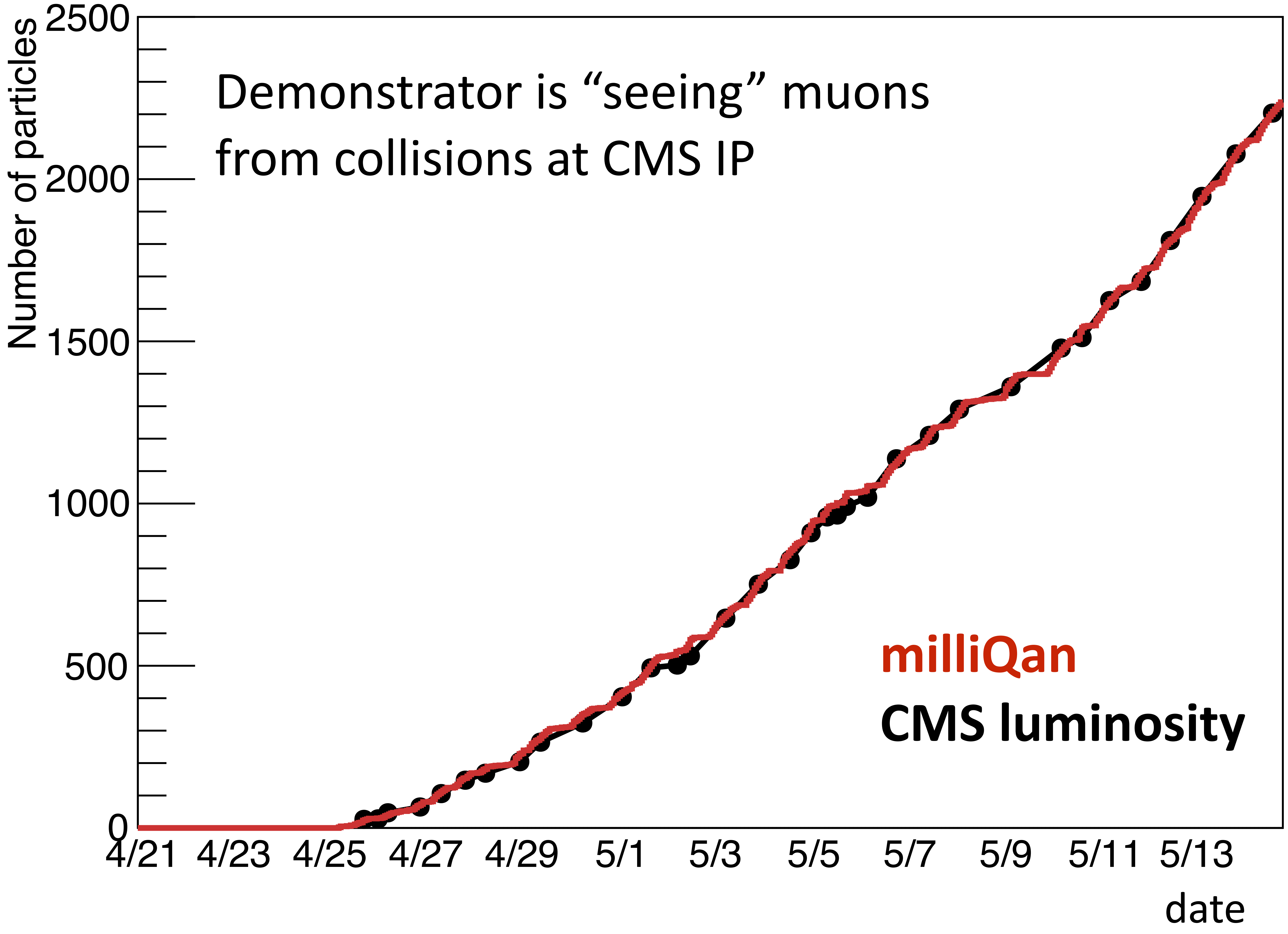


Demonstrator results: beam muon occupancy

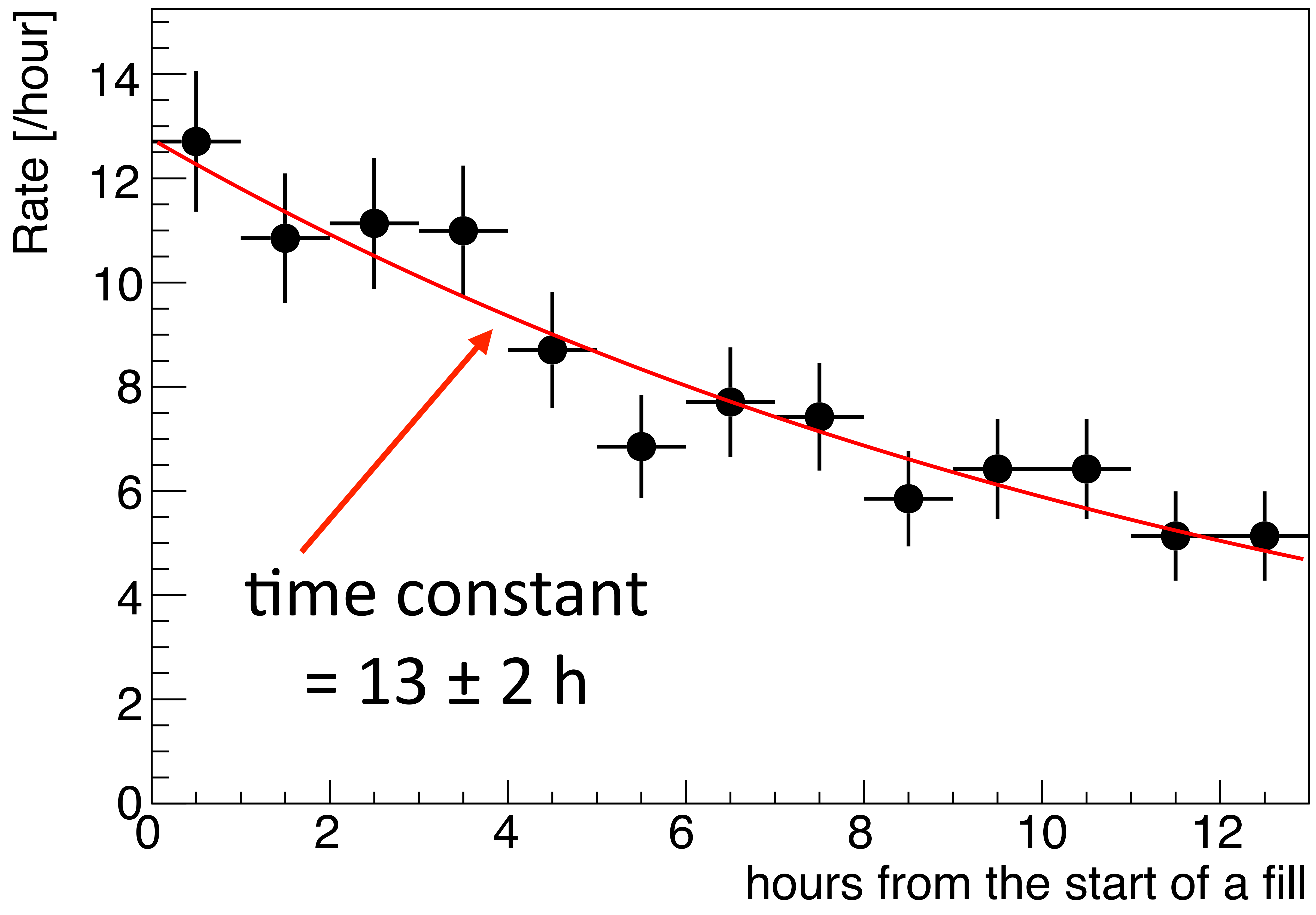




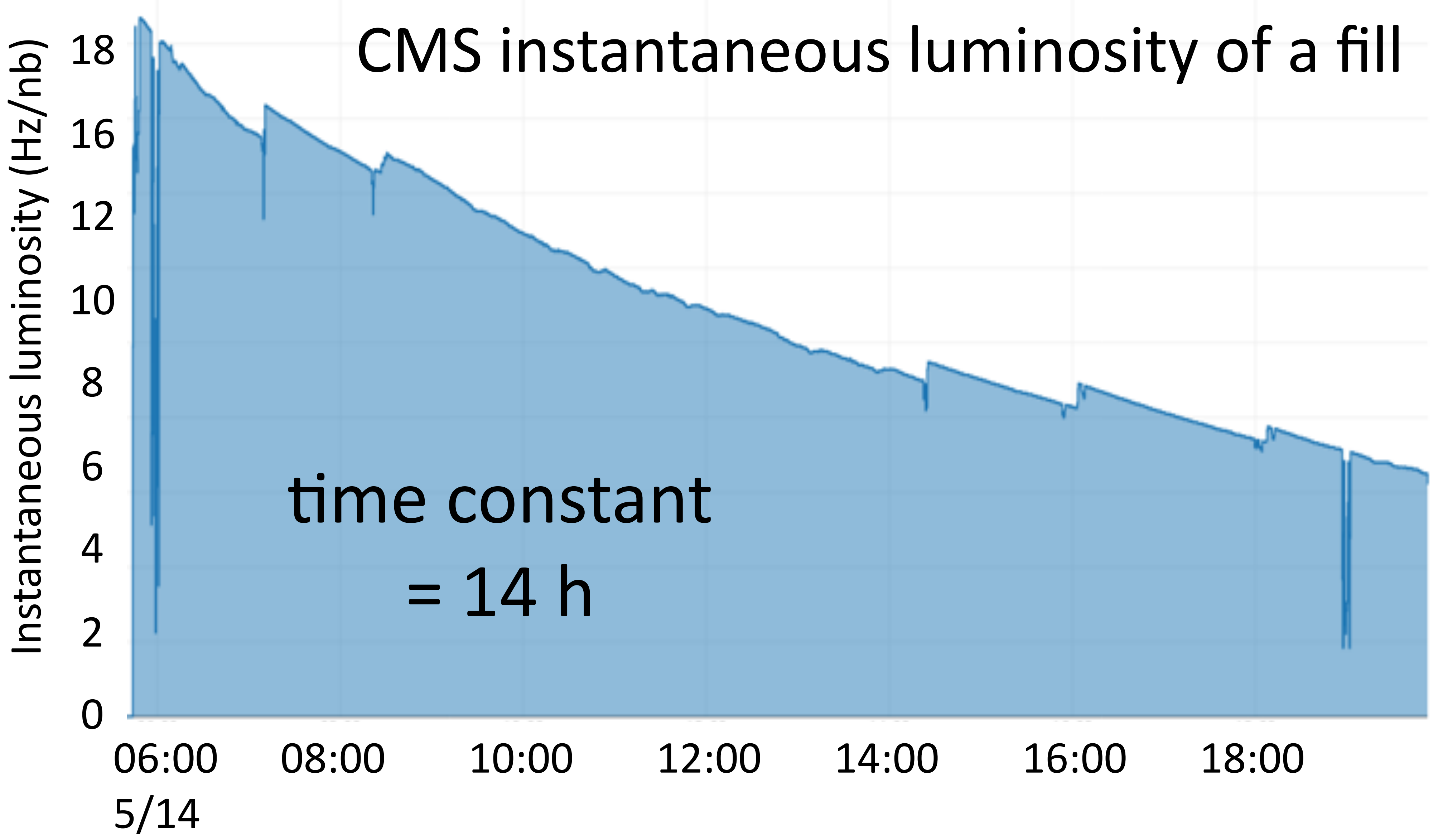
Demonstrator results: beam muon occupancy



Demonstrator results: luminosity structure within a fill

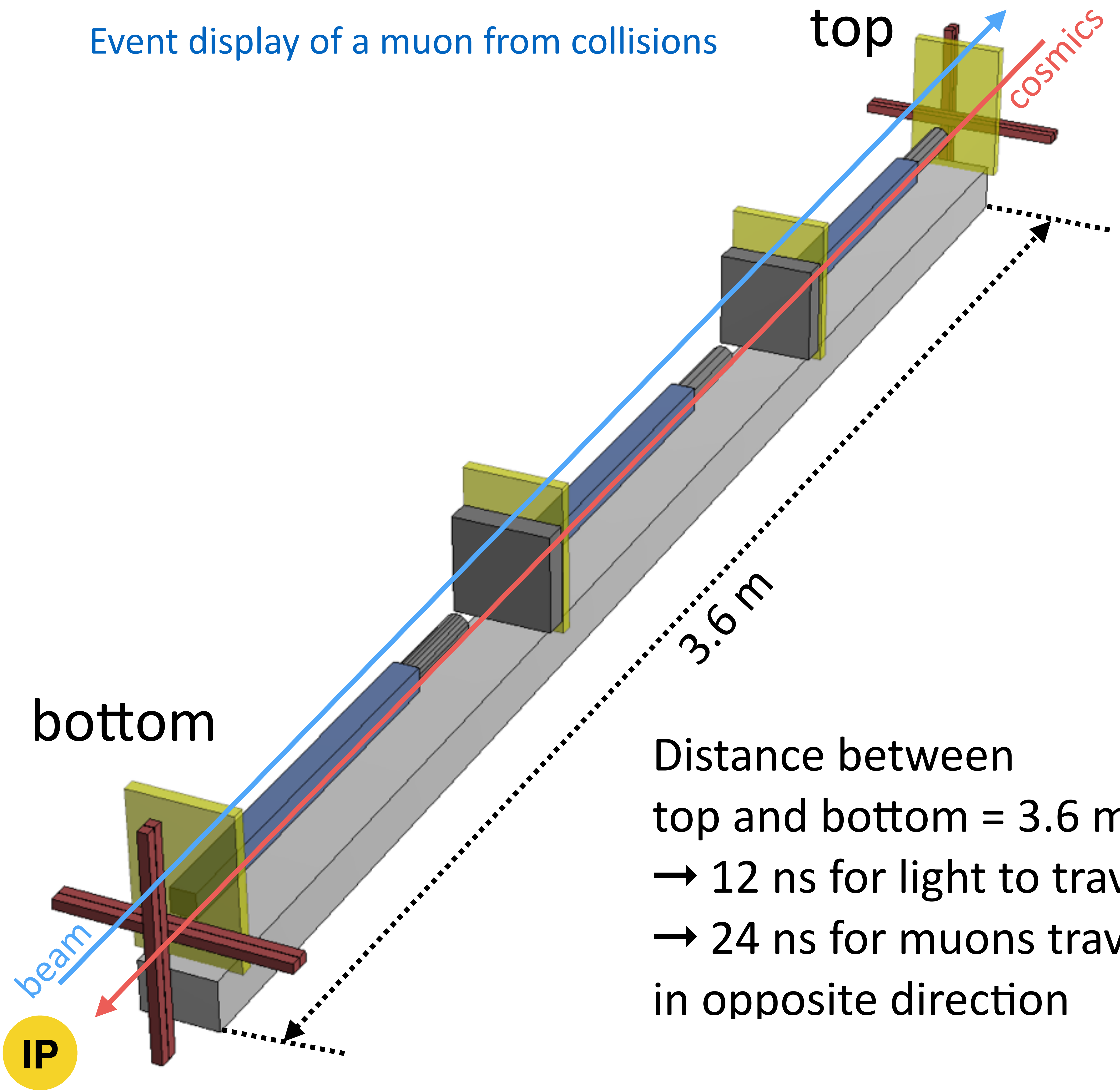


- Rate of thru-going particles as a function of time (hour)
- Rate decreases exponentially
  - consistent with trend of instantaneous luminosity (time constant: 13±2h vs 14h)

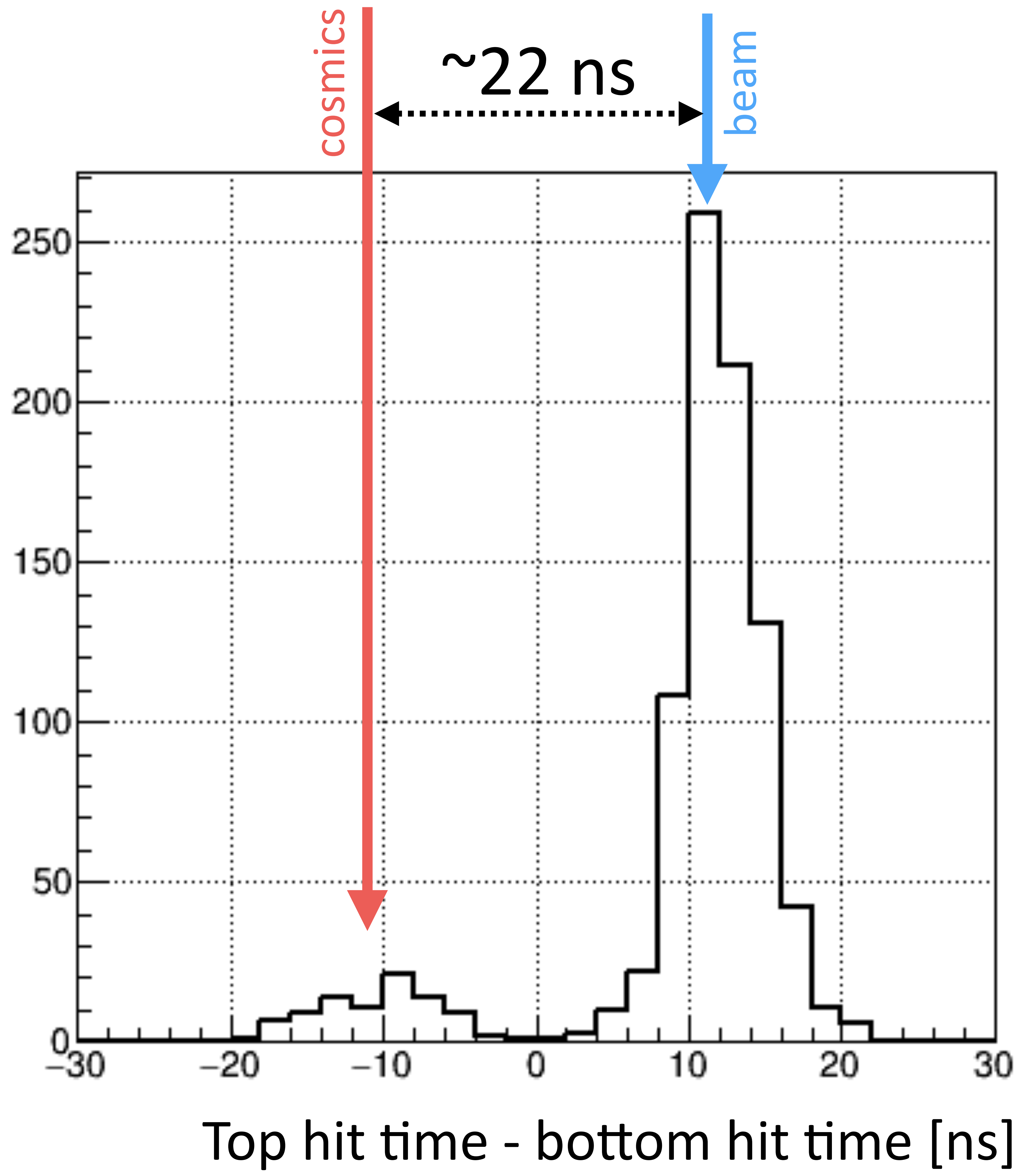


Demonstrator results: timing of thru-going particles

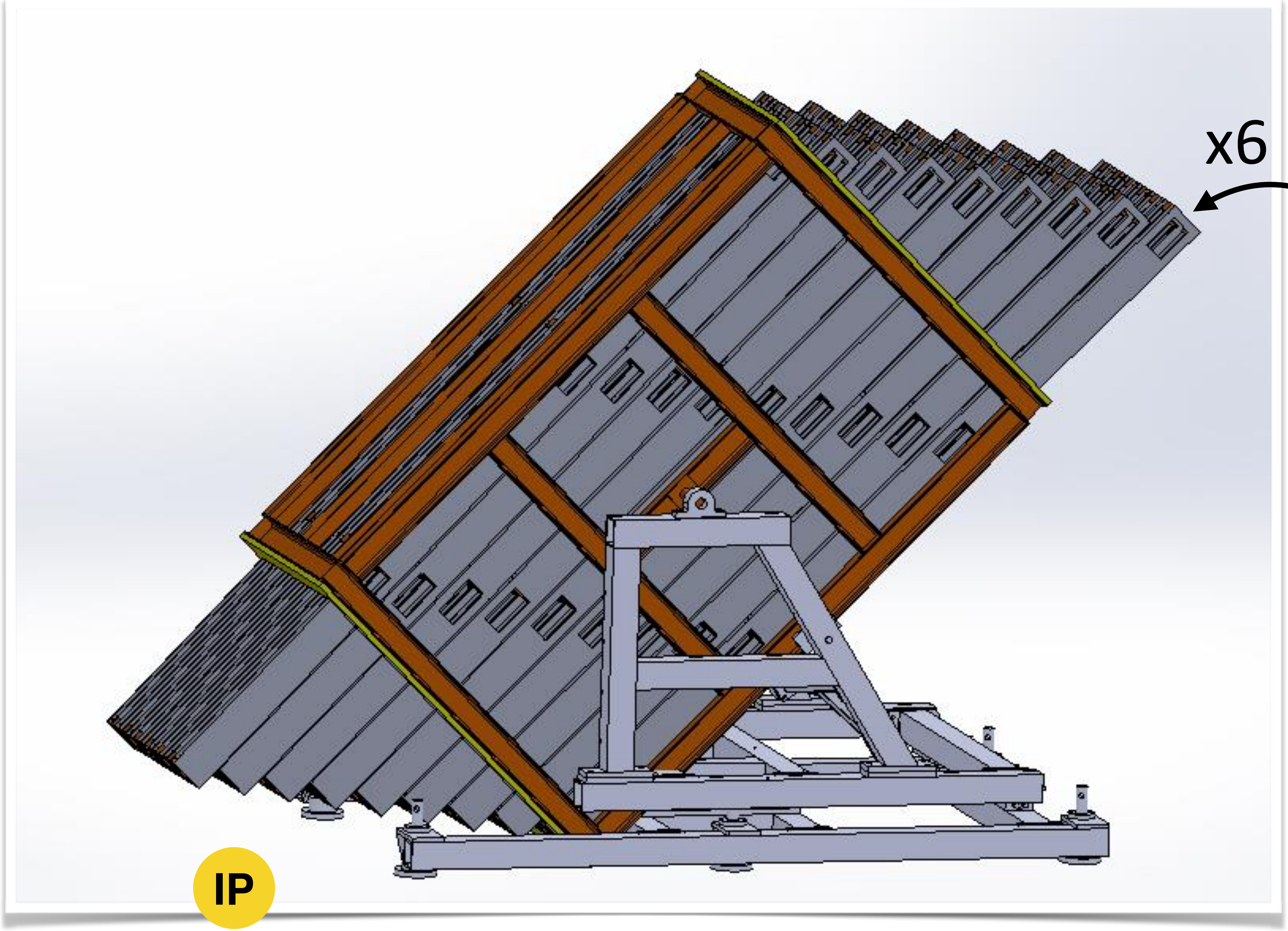
Event display of a muon from collisions

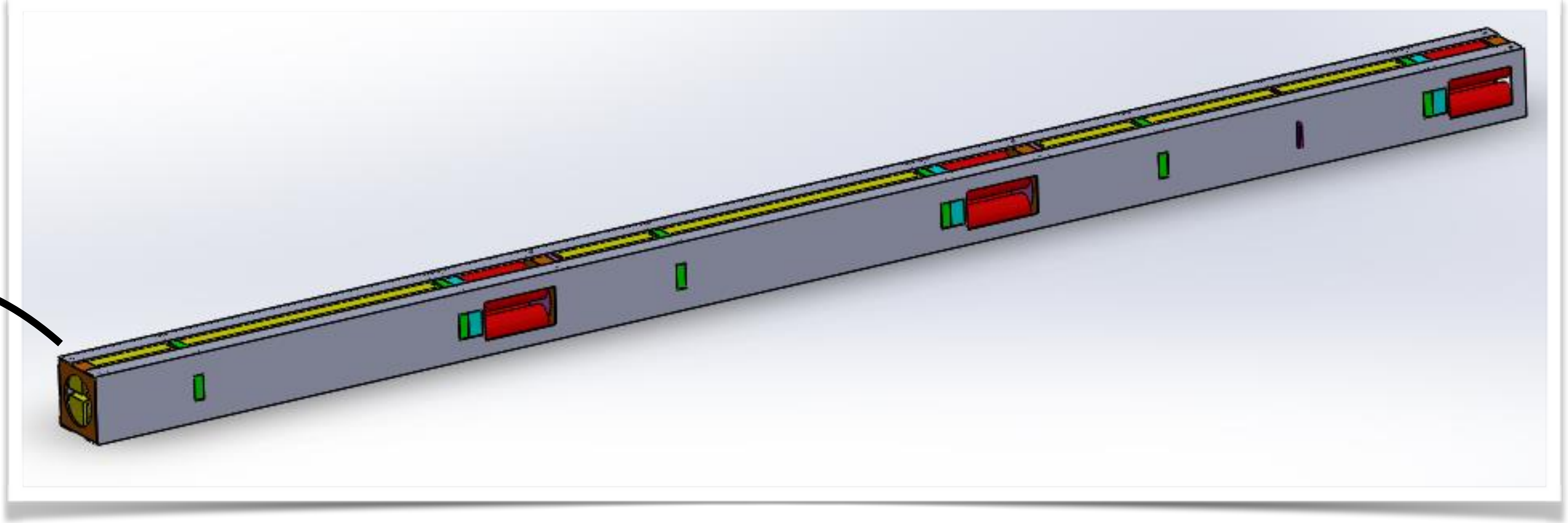


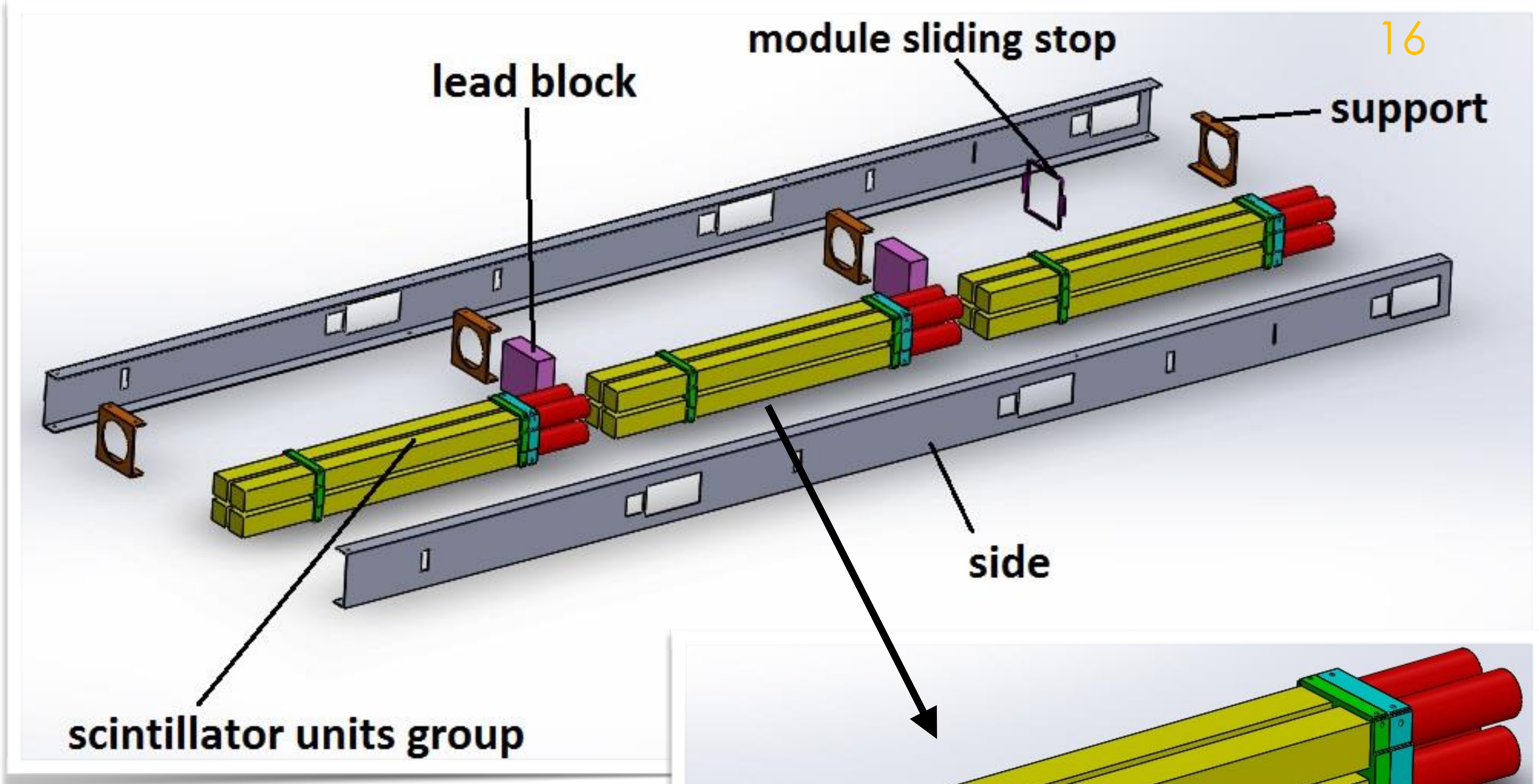
Distance between top and bottom = 3.6 m
→ 12 ns for light to travel
→ 24 ns for muons traveling in opposite direction

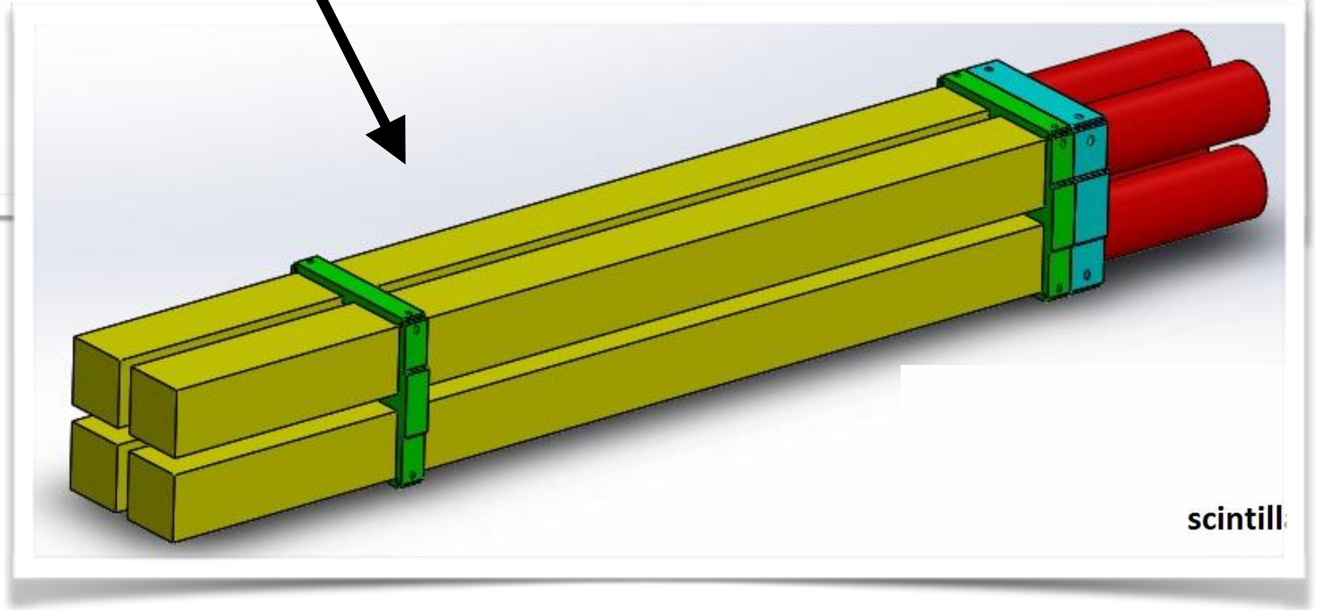


Mechanical design for full detector



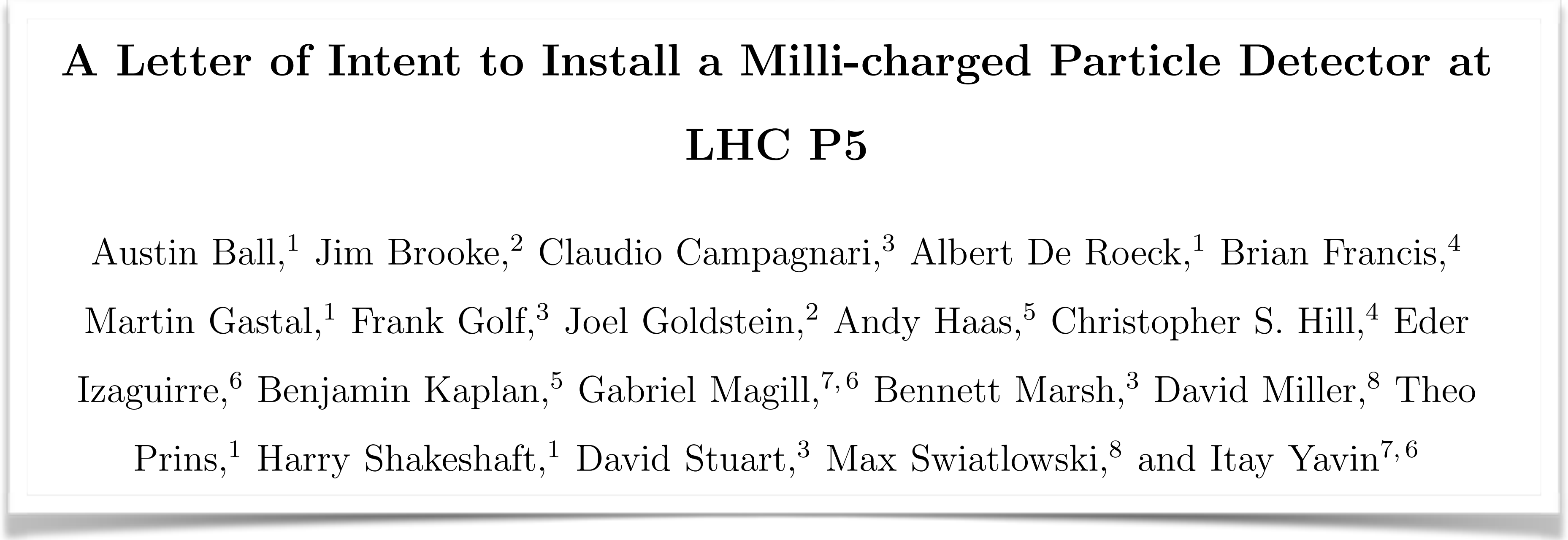




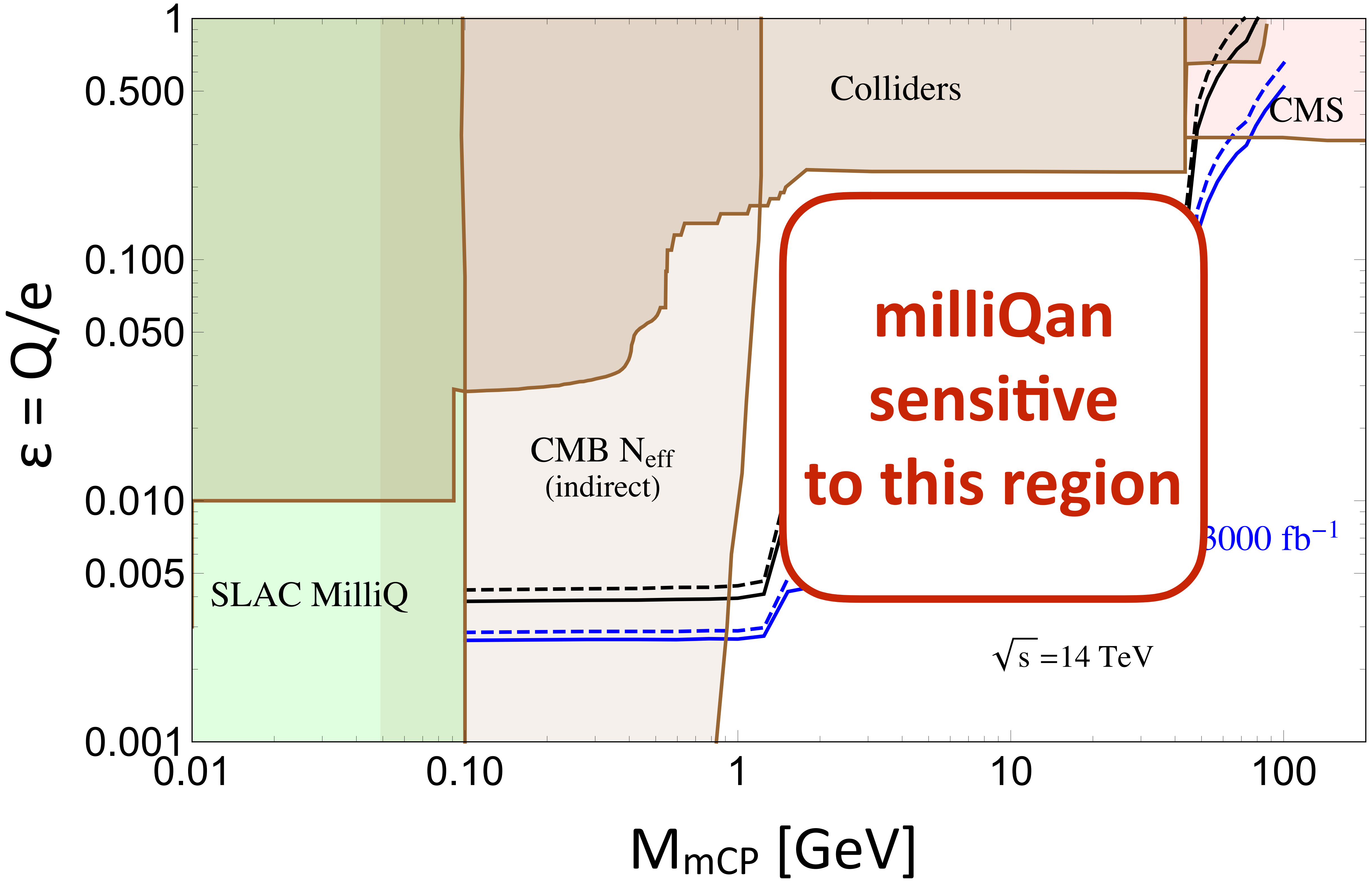


Due to spatial constraint, use 9-step form
Design well advanced and finalizing details

Summary and Plan


A Letter of Intent to Install a Milli-charged Particle Detector at LHC P5

Austin Ball,[1] Jim Brooke,[2] Claudio Campagnari,[3] Albert De Roeck,[1] Brian Francis,[4] Martin Gastal,[1] Frank Golf,[3] Joel Goldstein,[2] Andy Haas,[5] Christopher S. Hill,[4] Eder Izaguirre,[6] Benjamin Kaplan,[5] Gabriel Magill,[7,6] Bennett Marsh,[3] David Miller,[8] Theo Prins,[1] Harry Shakeshaft,[1] David Stuart,[3] Max Swiatlowski,[8] and Itay Yavin[7,6]



- milliQan experiment has a unique sensitivity to unexplored m_{mCP}=1-100 GeV and Q<0.3e region
- Demonstrator installed last year; being used to validate design and measure backgrounds
  - Learning a lot about background and gaining experience in detector operation
  - Demonstrator data might provide first sensitivity to the uncovered region
- Full detector is planned to be installed during LS2
  - Look forward to building and running it to discover nature's secret particle!

Backup

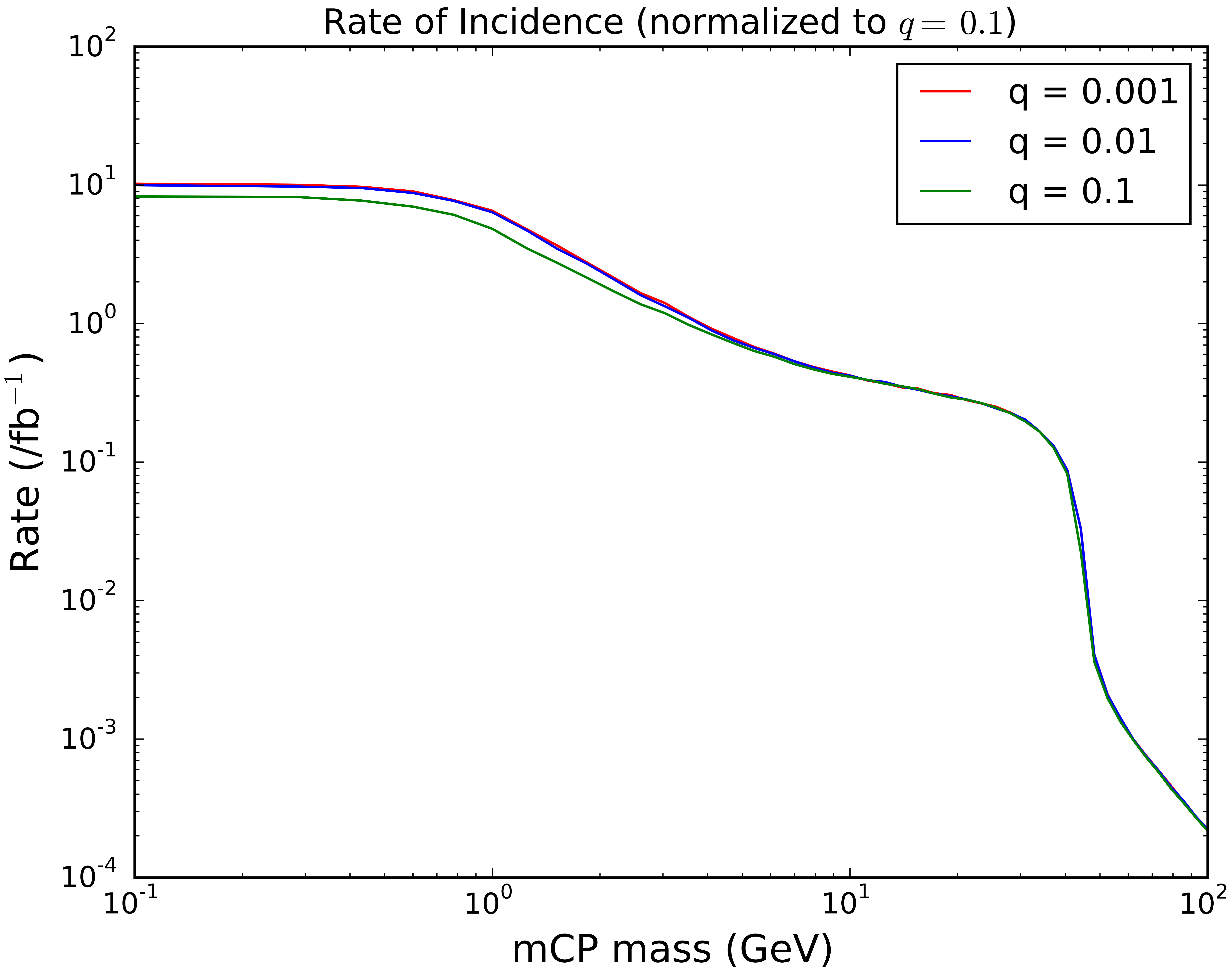
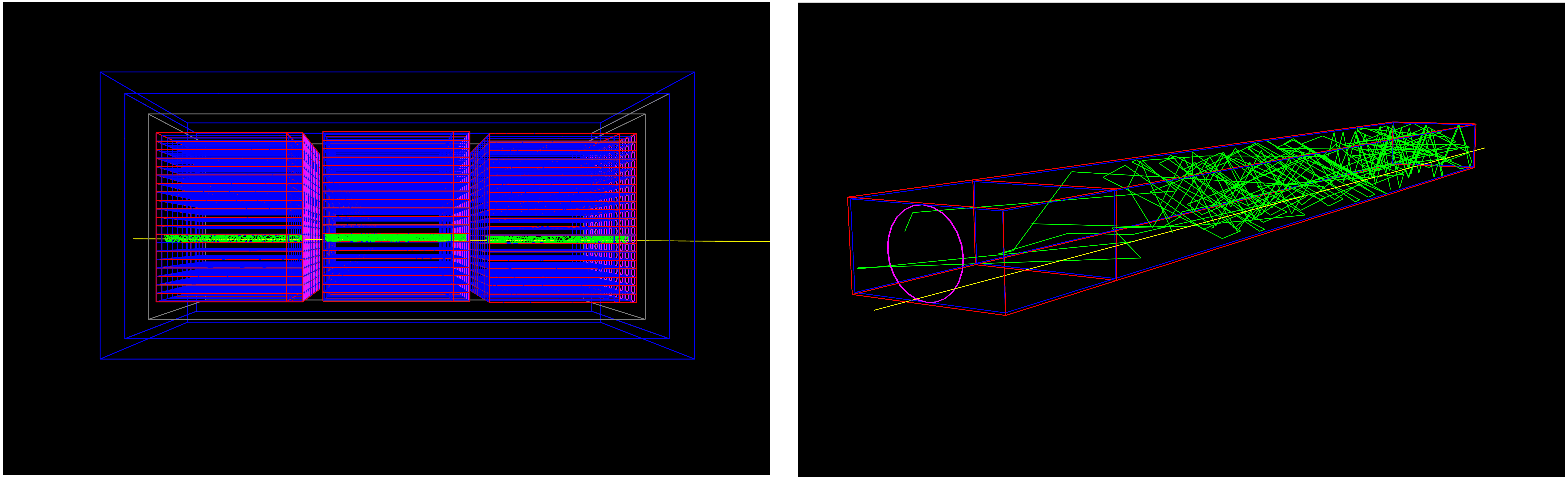


FIG. 4 in LOI

Number of expected mCP particles per fb^{-1} of integrated luminosity incident at the detector as a function of the mass of the milli-charged particle. To illustrate the dependence of the acceptance on the charge, the Q^2 production dependence has been factored out by normalizing the cross section for all charge scenarios to that for a milli-charged particle with Q = 0.1 e.

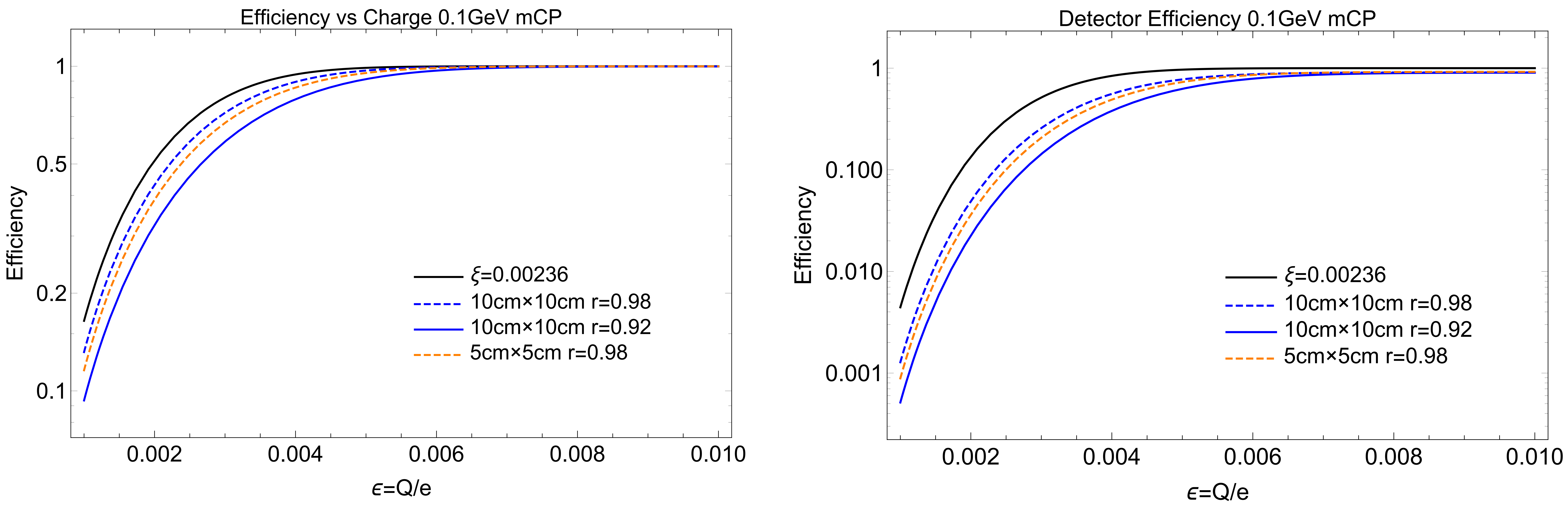
Geant4 simulation



(a) (b)

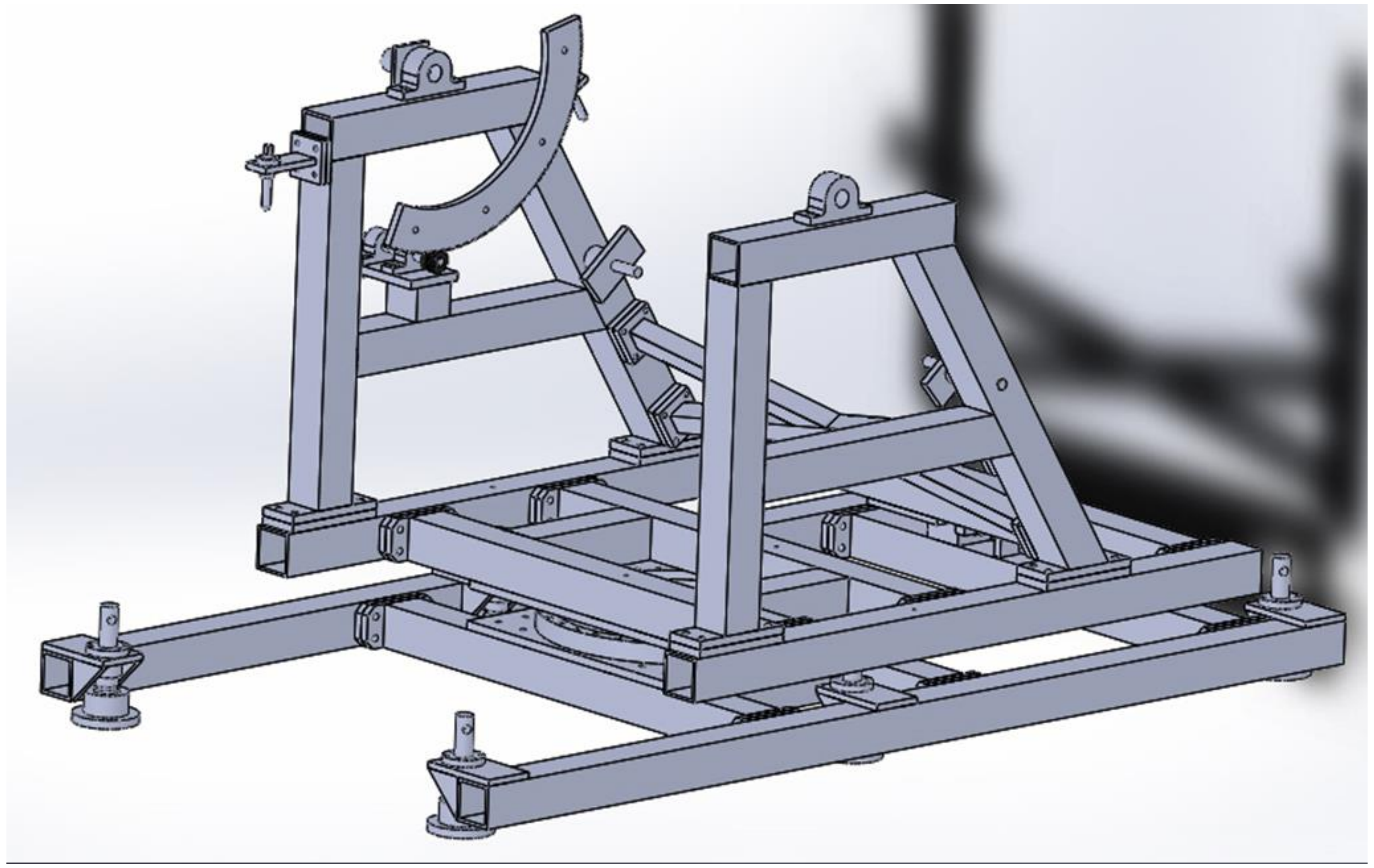
FIG. 5: Depiction of the (a) full detector and (b) a single scintillating block with coupled phototube, as implemented in the GEANT4 detector simulation. The mCP is yellow and radiated photons are green.

Detection efficiency

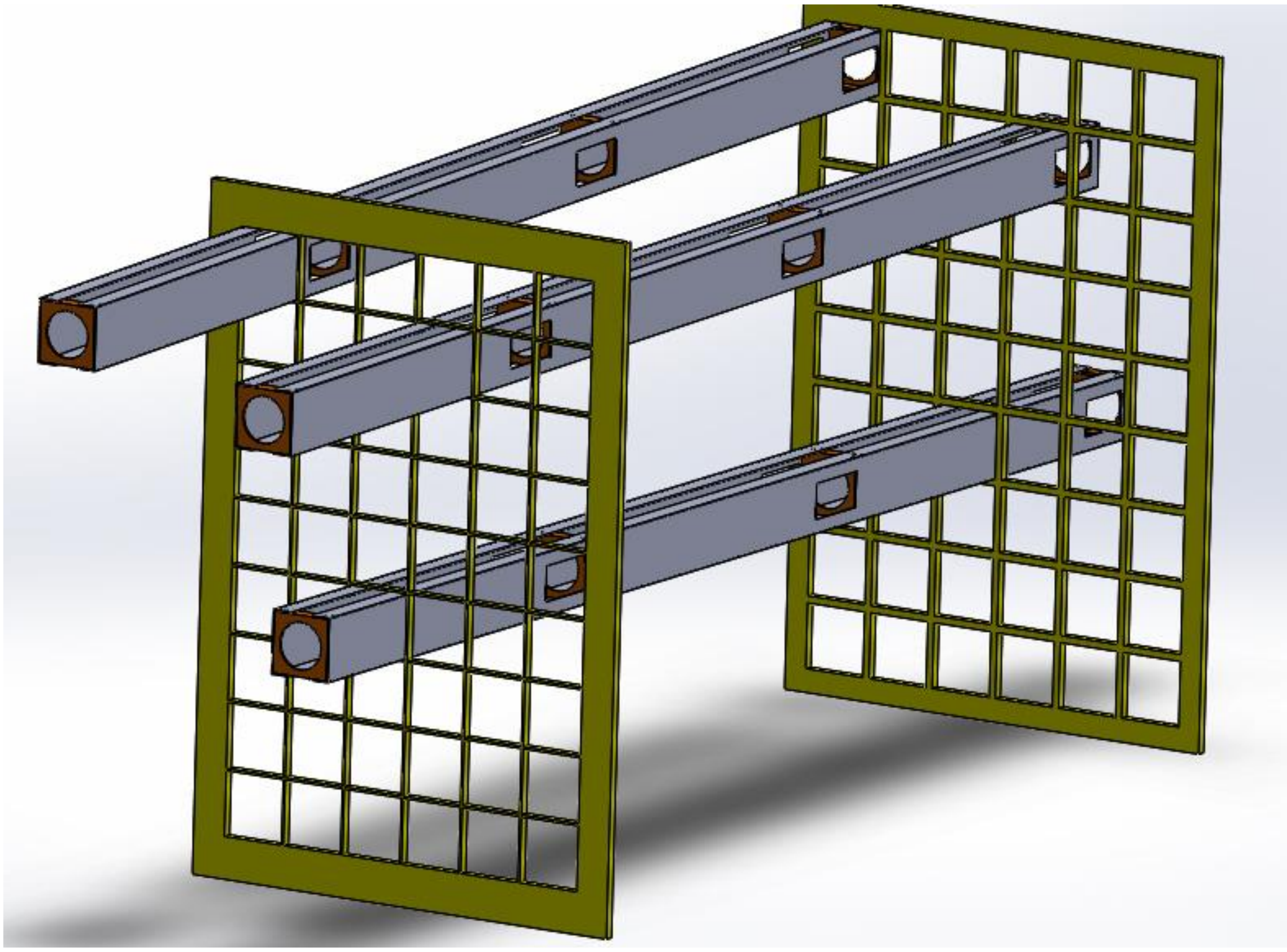


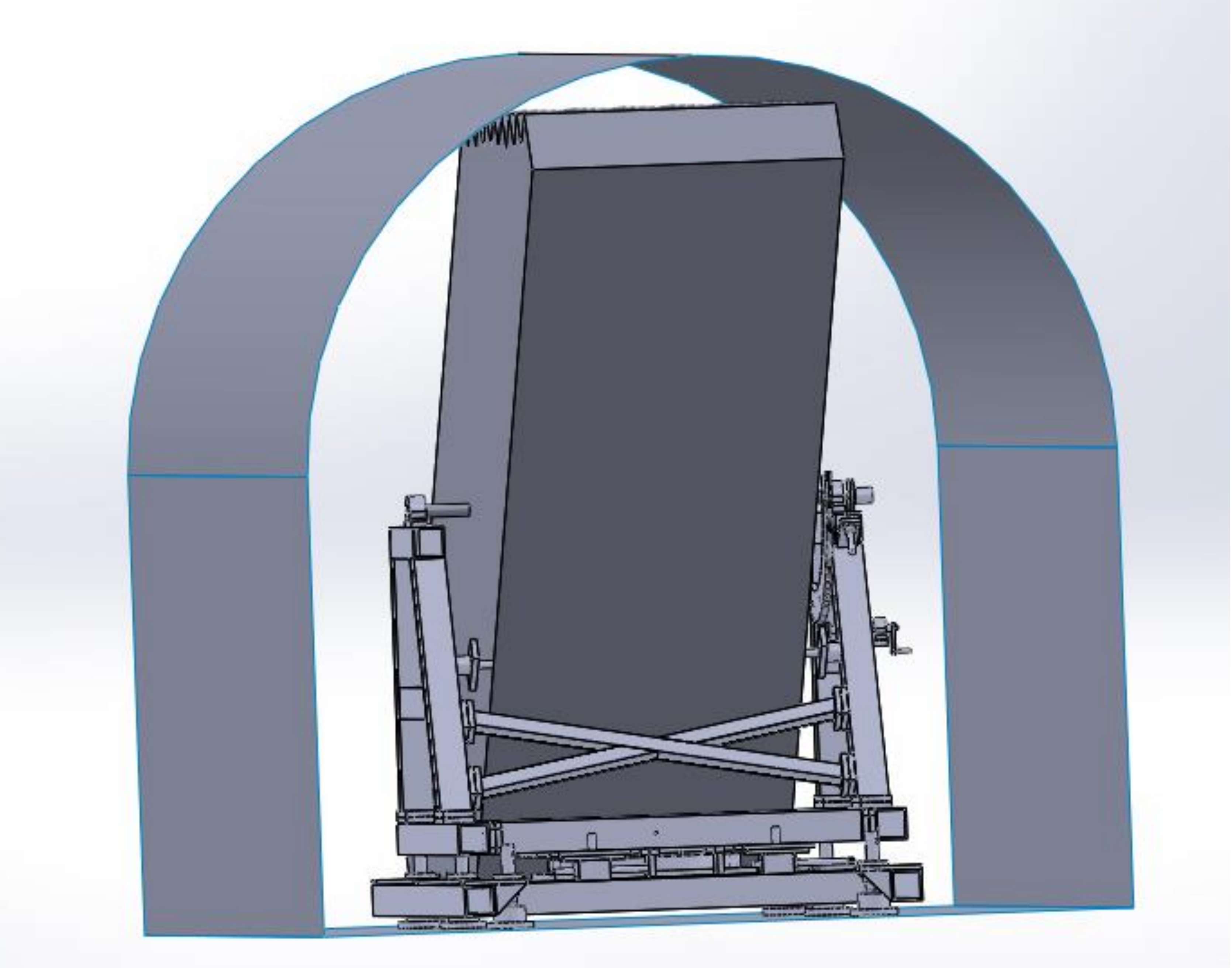
(a) (b)

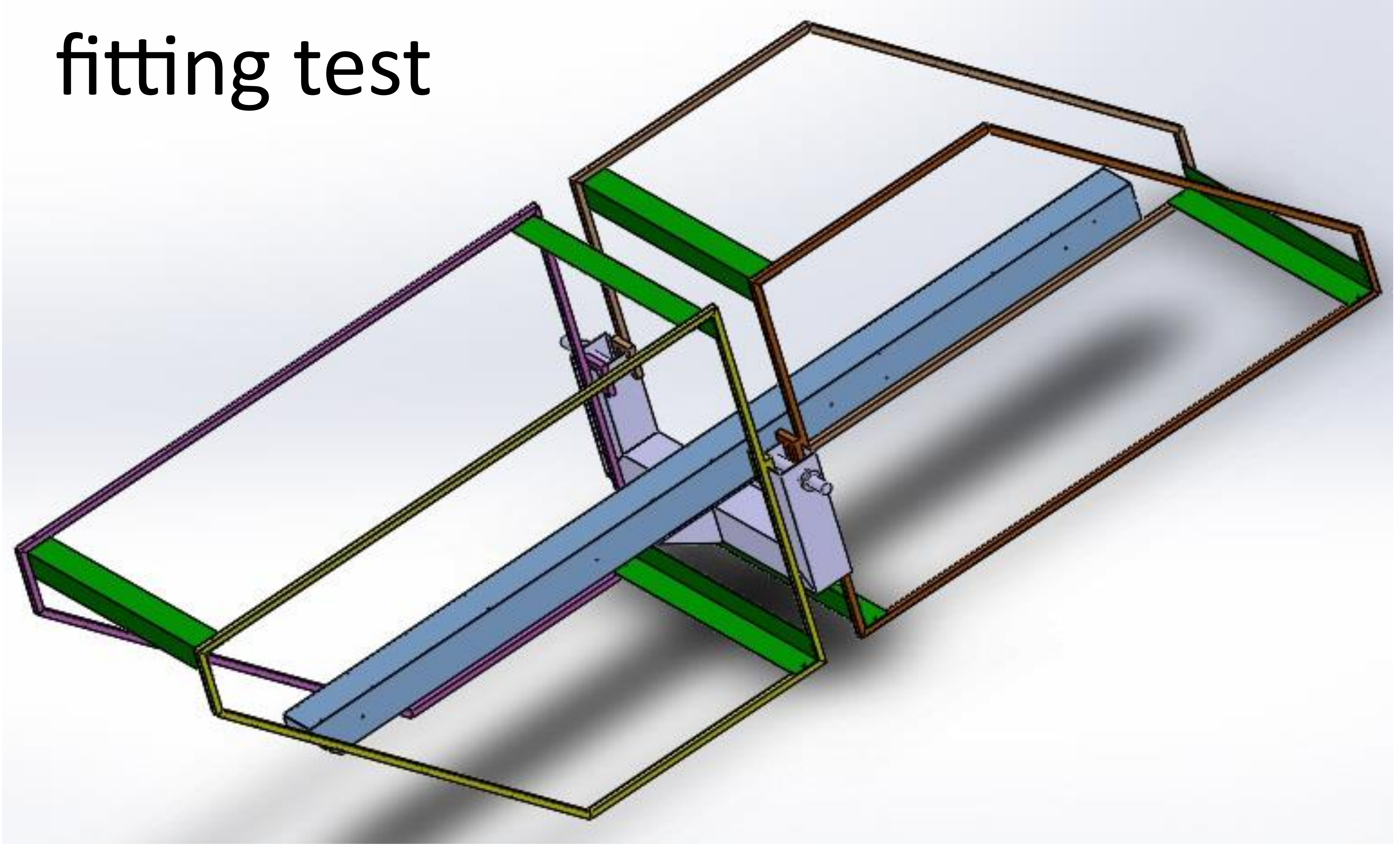
FIG. 6: Efficiencies for (a) a single scintillator block and coupled PMT and (b) the whole detector with 15ns triple-incidence, as determined from the GEANT4 detector simulation.

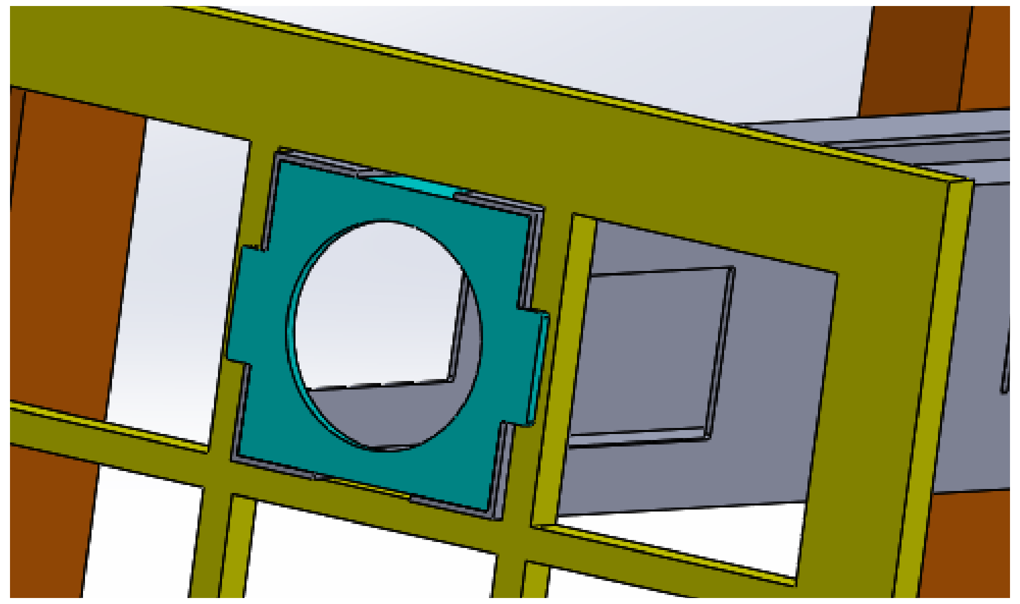


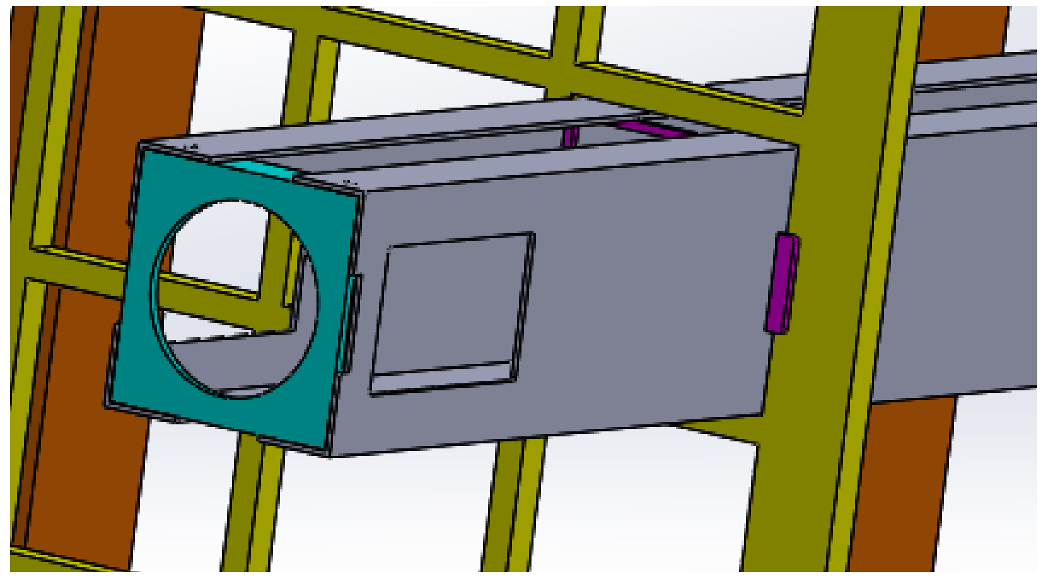

support structure
already installed

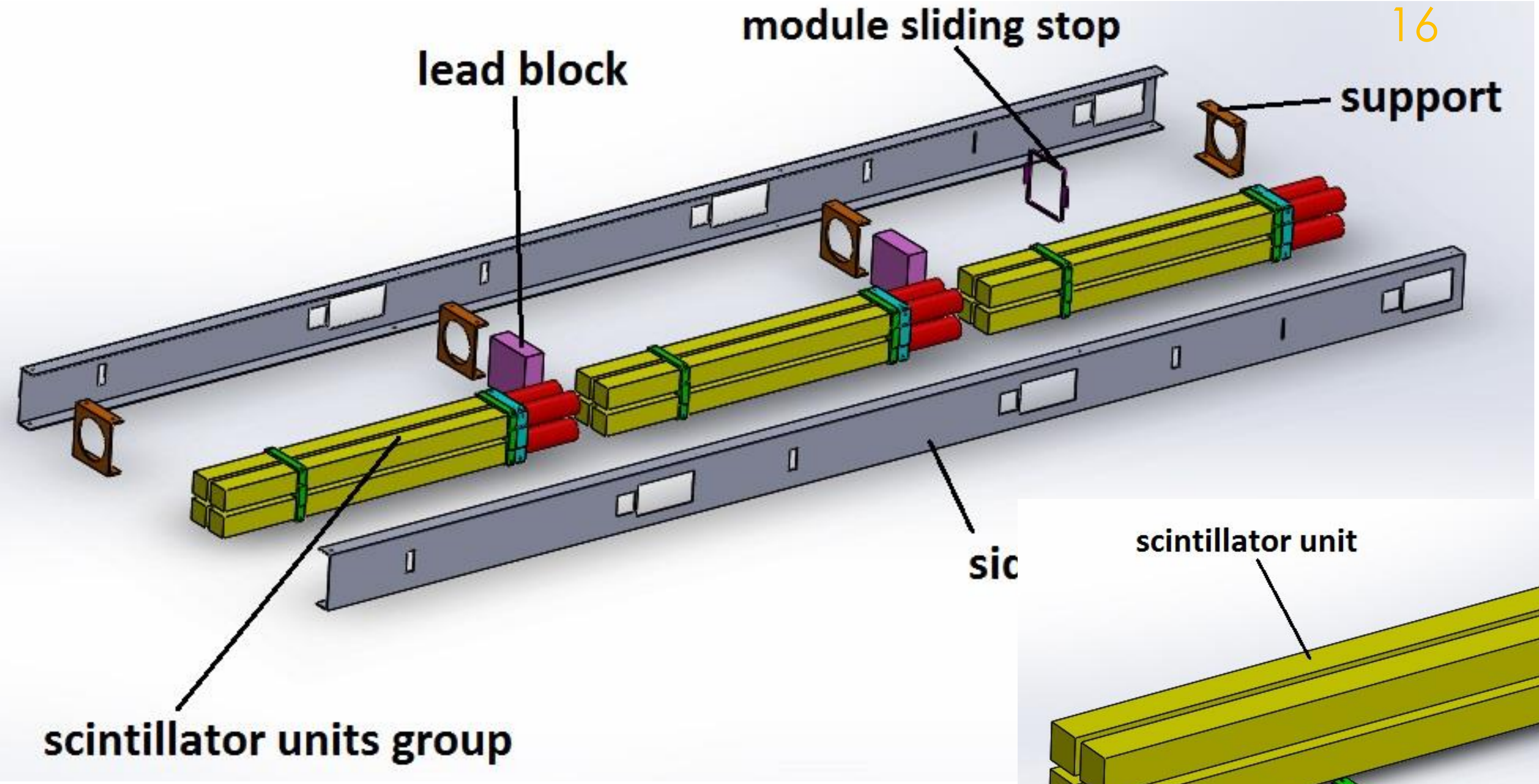


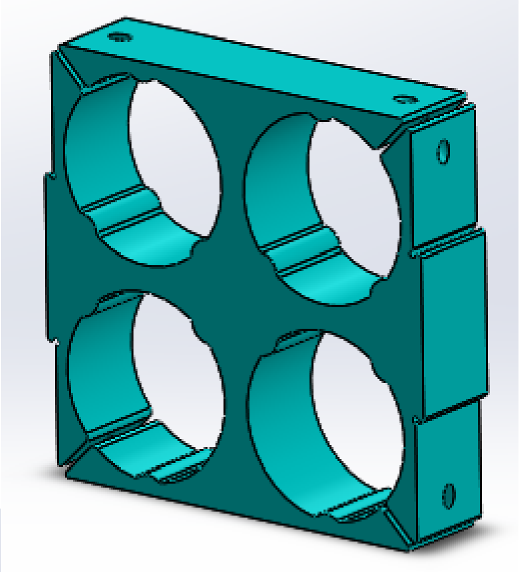


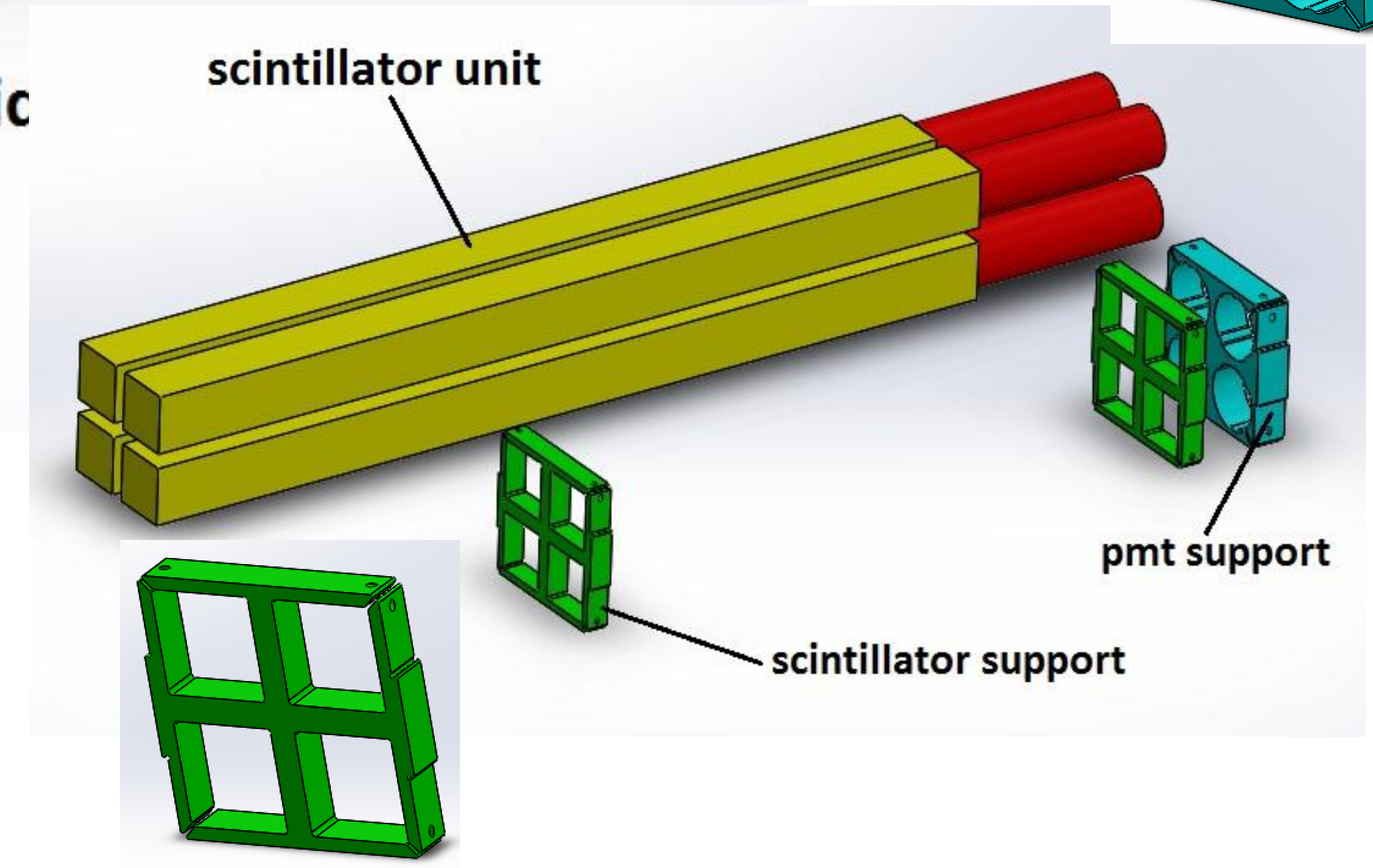

fitting test

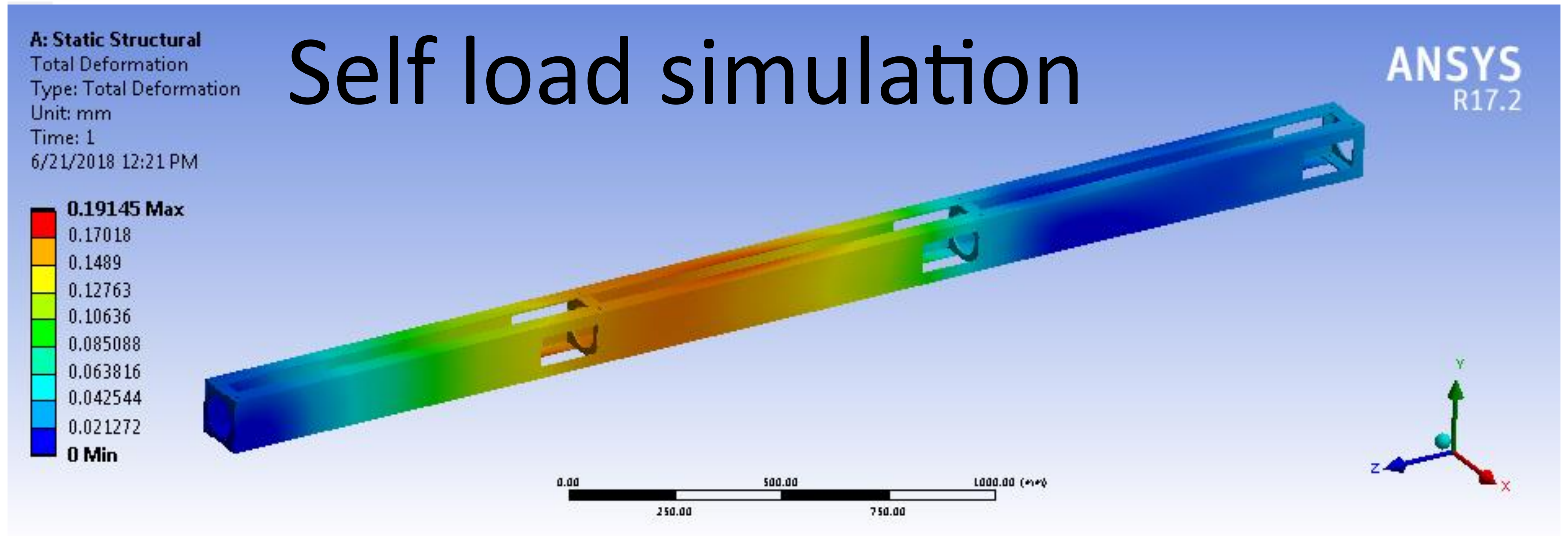




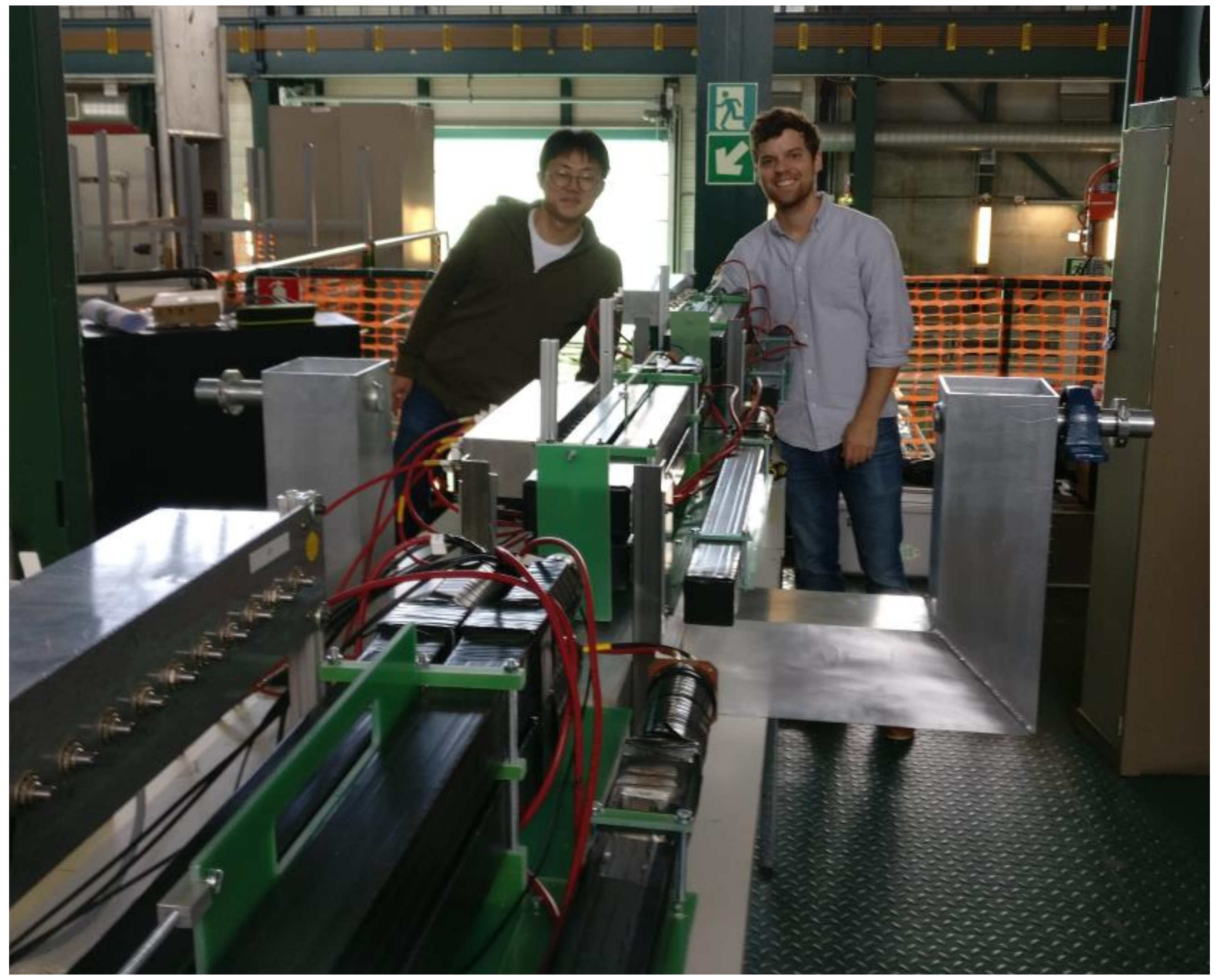

16
module sliding stop
lead block
support
scintillator units group

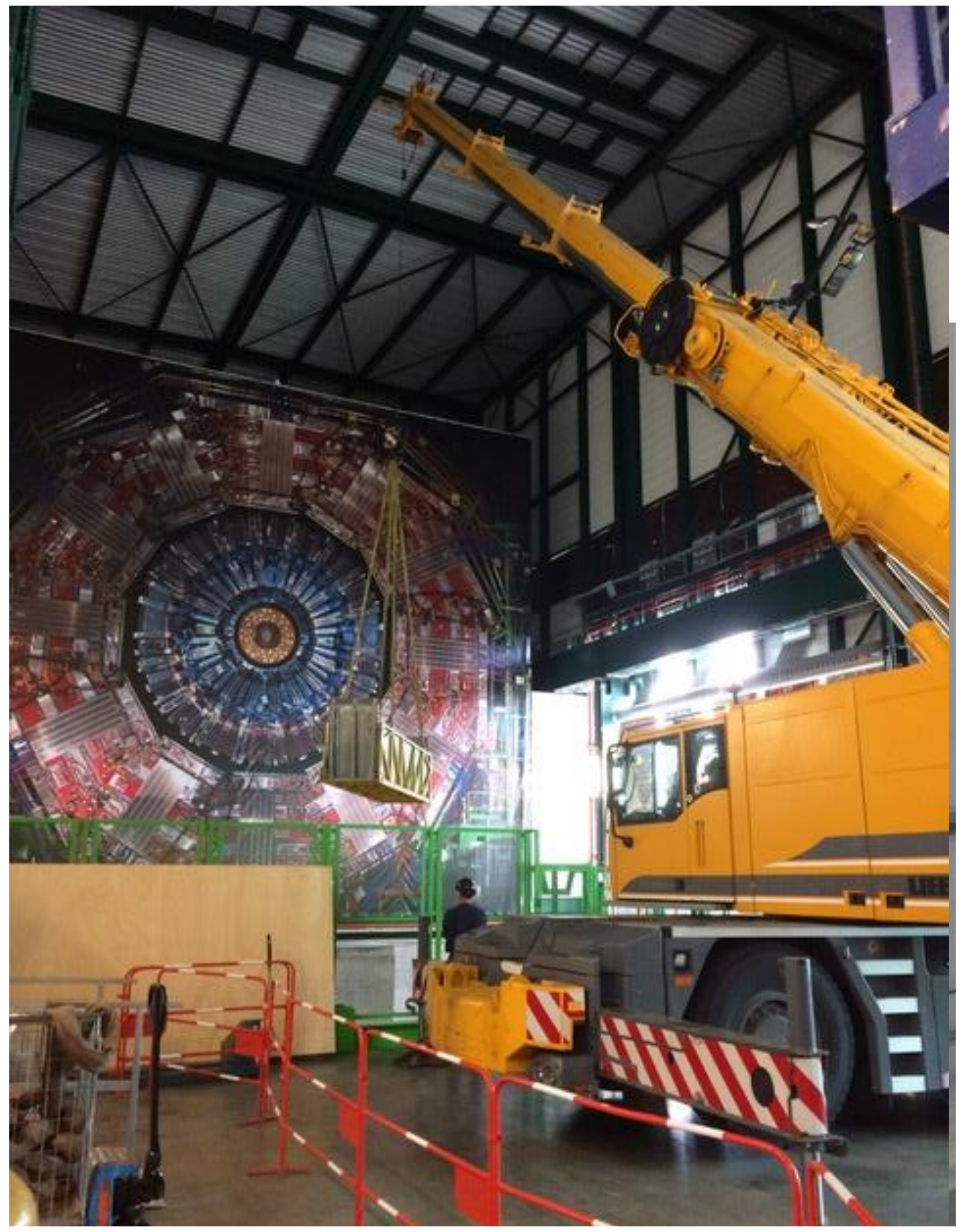


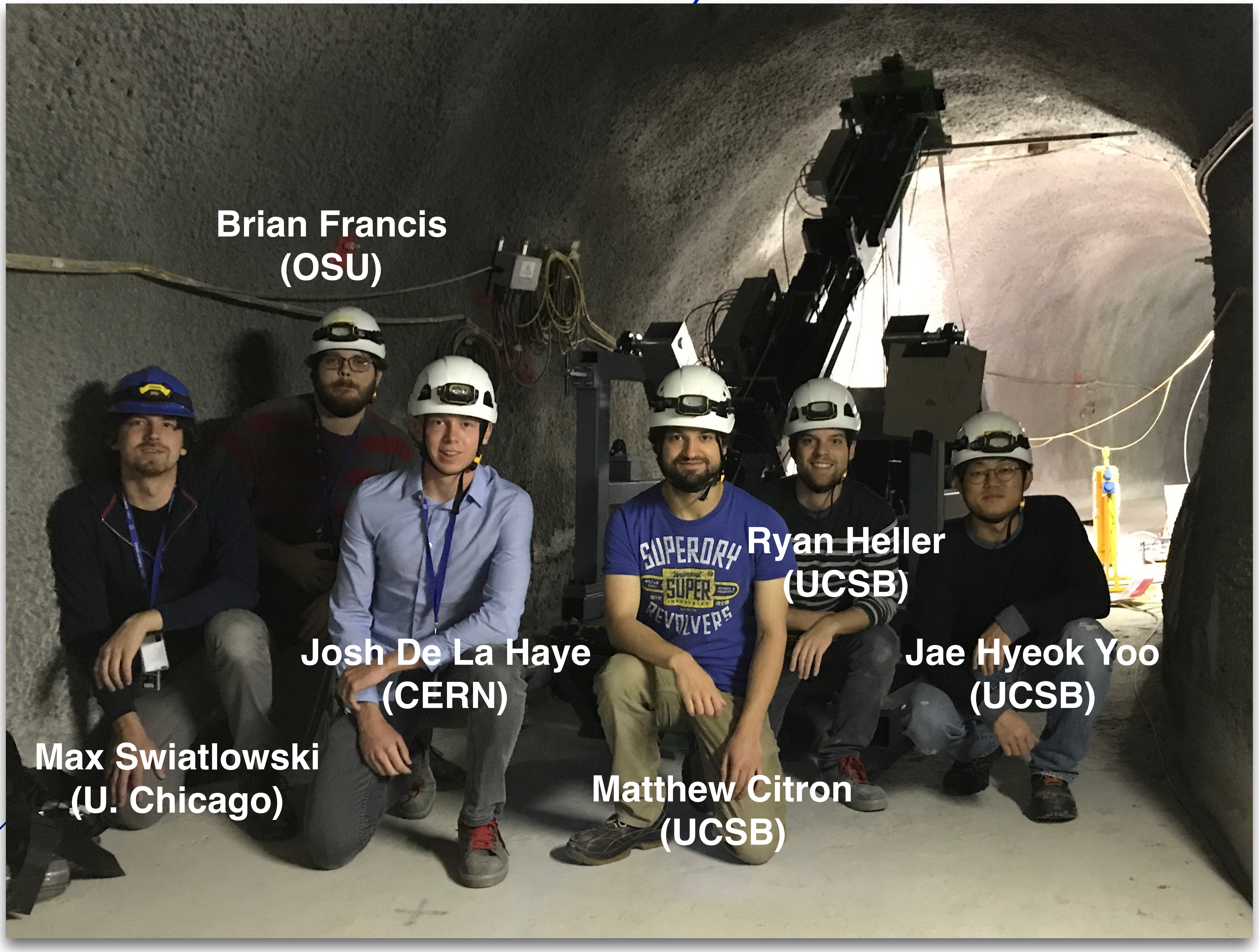

scintillator unit
pmt support
scintillator support


Self load simulation
A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
6/21/2018 12:21 PM
0.19145 Max
0.17018
0.1489
0.12763
0.10636
0.085088
0.063816
0.042544
0.021272
0 Min
ANSYS
R17.2

Installation of demonstrator



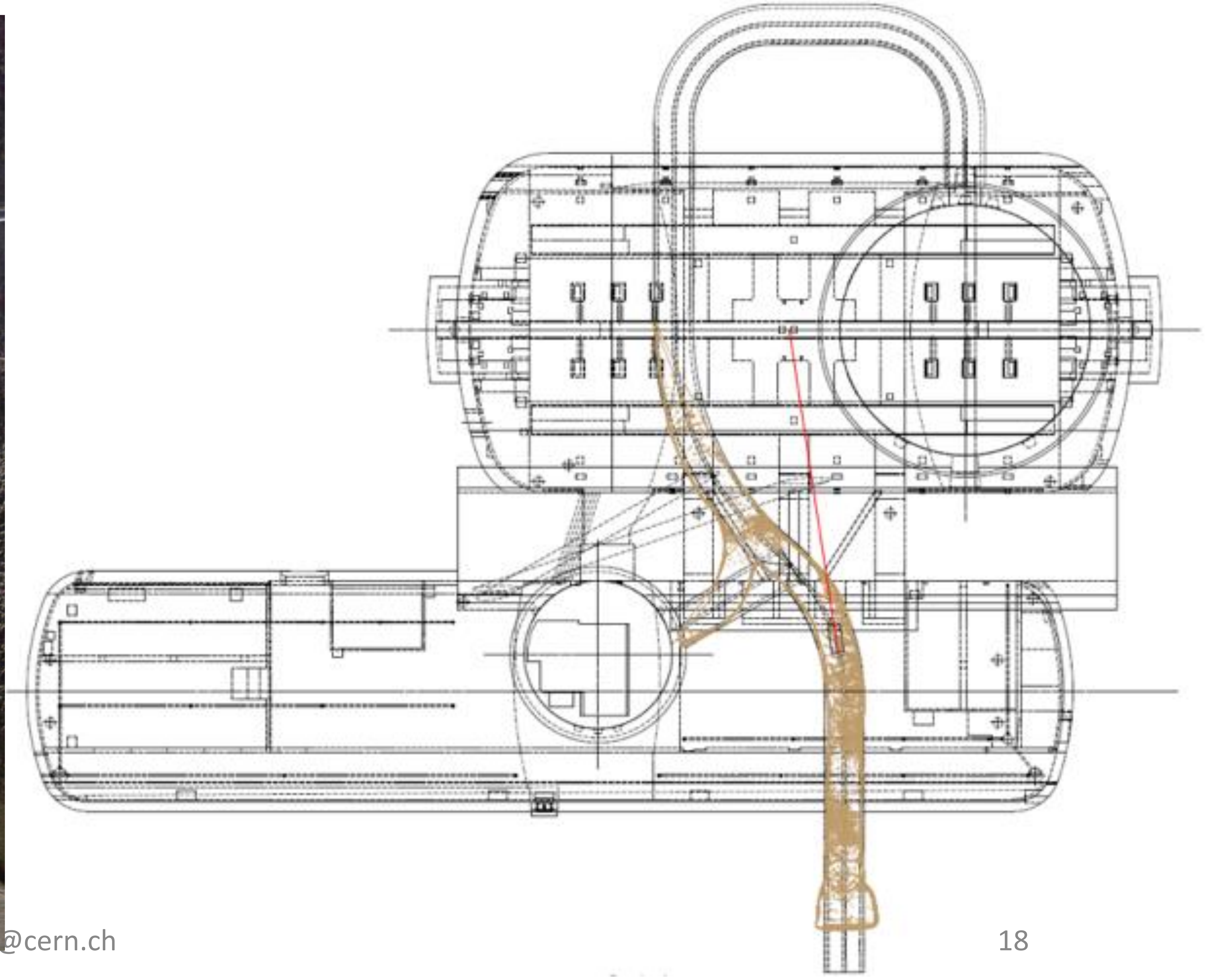




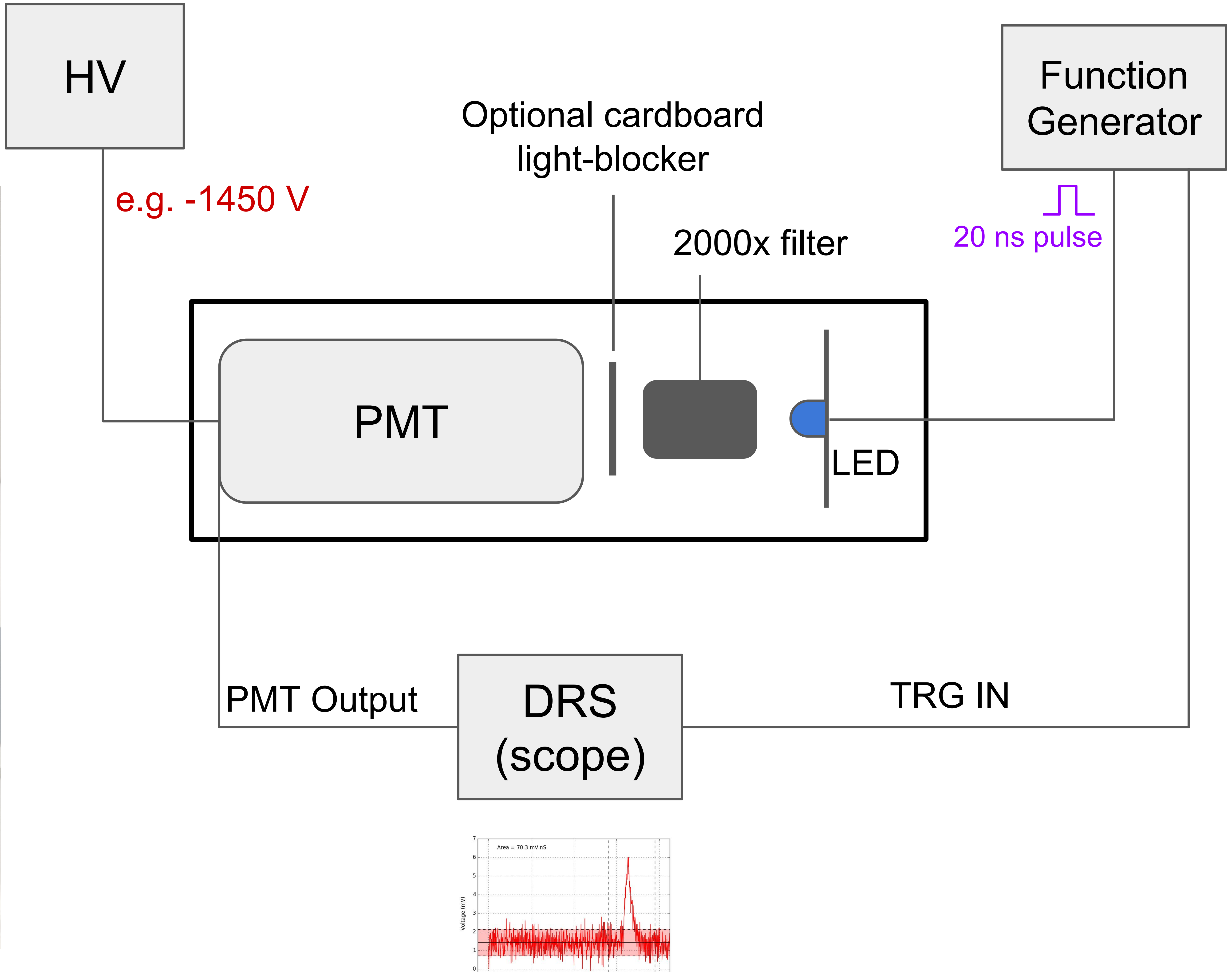
Installation team in front of the demonstrator

Alignment of demonstrator

- The detector had to be aligned with CMS IP
  - Projection of CMS network into gallery done during TS1
  - Alignment of detector carried out by Noemie Beni and Benoit Cumer



Charge calibration: bench setup



Can control ⟨N_{PE}⟩ by varying amplitude of input LED pulse

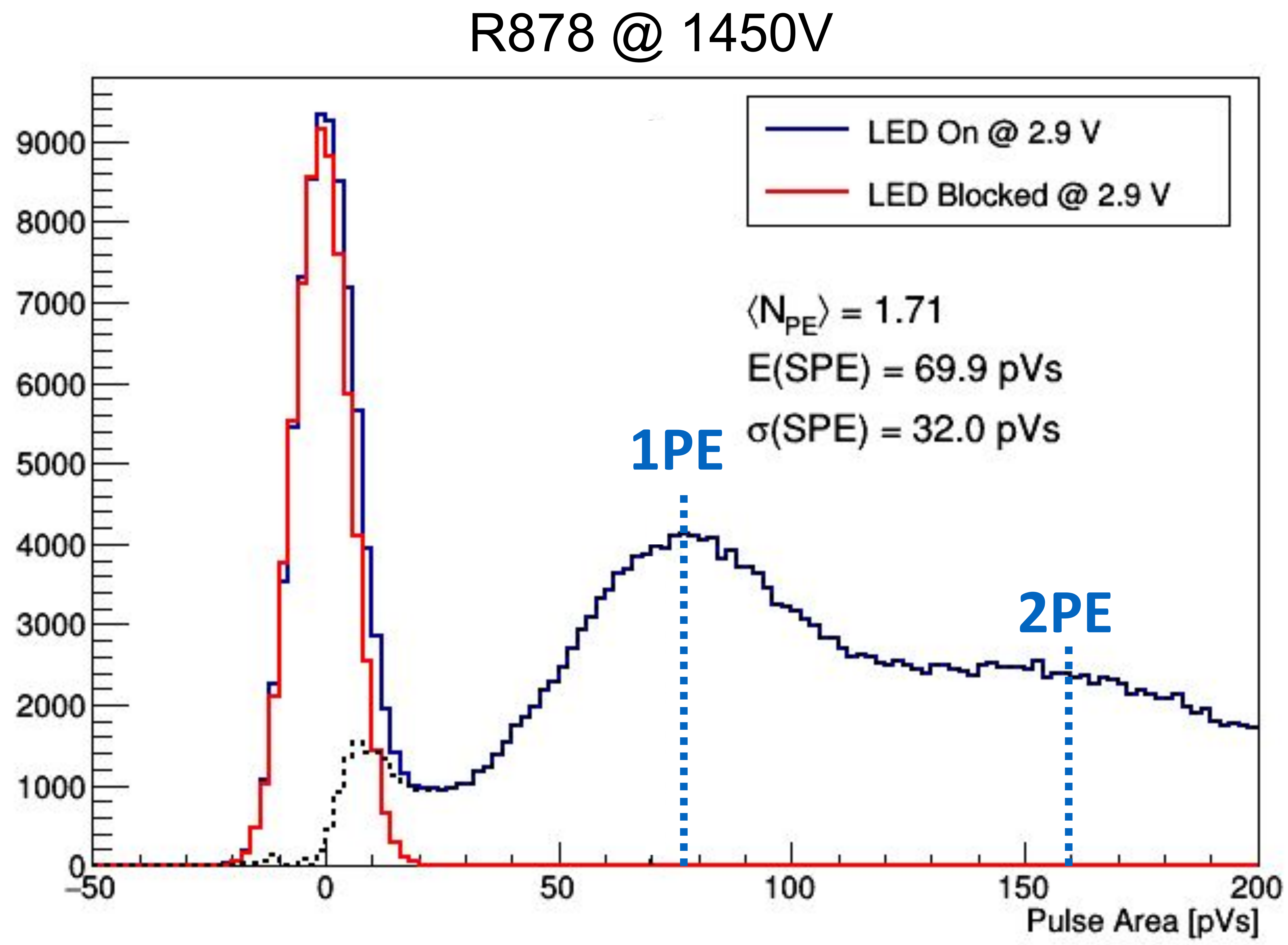
Trigger scope on the LED pulse, so PMT response falls in well-defined time window

No need for any peak-finding, and allows us to trigger on "blank" (0-PE) events

LED:
Thorlabs LED430L
430 nm (blue/violet)

PMTs:
Hamamatsu R878
Hamamatsu R7725

Charge calibration: bench results



1PE peak at 80 pVs

milliQan collaboration

David Stuart (UCSB)

Claudio Campagnari (UCSB)

Frank Golf (U of Nebreska)

David Miller (U of Chicago)

Chris Hill (OSU)

Andy Haas (NYU)

milliQan collaboration

David Stuart (UCSB)

Ryan Heller (UCSB/Fermilab)

Max Swiatlowski (U of Chicago)

Brian Francis (OSU)

Matthew Citron (UCSB)

Jae Hyeok Yoo (UCSB)

Note in photo: Ralf Ulrich (KIT), Austin Ball, Albert De Roeck, Martin Gastal, Rob Loos (CERN), Maytham Ezzeldine, Haitham Zaraket (Univerisite Libanaise), Itay Yavin, Gabriel Magill (Perimeter/McMaster), Edar Izaguirre (BNL), Jim Brooke, Joel Goldstein, Olivier Davignon (Bristol)